IN-SITU RESOURCE UTILIZATION GAP ASSESSMENT REPORT

4/21/2021

International Space Exploration Coordination Group

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EXECUTIVE SUMMARY

In 2019, the Technology Working Group (TWG) of the International Space Exploration Coordination Group (ISECG) established a Gap Assessment Team (GAT) for the topic of In-Situ Resource Utilization (ISRU). The ISRU GAT Assessment is intended to examine and identify technology needs and inform the ISECG on technology gaps that must be addressed in order to implement foreseen missions. Ultimately, this initiative intends to create international dialogue among experts and inform agency decisions when considering investments is specific exploration technologies, while identifying potential collaboration opportunities. The following sections are an executive summary of the main sections of the full report.

Strategic Knowledge Gaps Definition

To help ensure that plans for human exploration of the Moon would be successful, an assessment was made to determine the state of human exploration technologies and capabilities. Where insufficient knowledge and/or capability was found, a statement of need was created. From this effort, a list of what became known as Strategic Knowledge Gaps (SKGs) was created in three broad themes of exploration, of which ISRU is relevant to the first and third theme. Since then, the SKGs have been reviewed and used to guide and prioritize development and flight activities for human exploration of the Moon. At the start of this effort, the In-Situ Resource Utilization (ISRU) Gap Assessment team reviewed the last approved SKG list with respect to ISRU technologies, capabilities, and operations in four major resource/function areas (polar water, solar wind volatiles, oxygen/metals from regolith, and construction and manufacturing) and the overall operation of any ISRU capability. From this effort, a table was created that establishes the potential impact the SKG has on each of the 4 major resource/function areas and ISRU operations, how/where the SKG will be closed, and when in the three-phase human lunar exploration architecture the SKG needs to be closed. The intent of this table (Table 3) is to allow decision-makers and developers to prioritize and plan the closure of these SKGs to achieve the desired ISRU capability and product.

ISRU Functional Breakdown and Flow Diagram

The identification, extraction, processing, and use of space resources will require a significant amount of technology, system, and capability development across a wide field of technical disciplines. The end-to-end process from resource identification to product delivery will also require a significant number of sequential and parallel steps. To ensure that all the technologies and processes have been properly identified and addressed throughout the end-to-end sequence from 'prospecting to product', the ISRU Gap Study team created two sets of tables/figures. The first set of tables examines the scope and breakdown of each of the three main ISRU capabilities examined in the study: 1) In-Situ Propellant and Consumable Production, 2) In-Situ Construction, and 3) In-Space Manufacturing with ISRU-derived Feedstock. For each of these three main ISRU capabilities, the major functions required to successfully implement the capability were defined and as well as the subfunctions associated with each of these major functions (depicted in Figures 3, 4, & 5). While these tables allow decision-makers and developers to define, address, and track past and on-going activities to successfully implement ISRU, the tables do not provide insight on how each of these functions and subfunctions may influence or be influenced by other areas of ISRU. To provide this level of insight, an integrated ISRU functional Flow Diagram was created (Figure 6). The figure allows decision-makers and developers to understand where gaps or deficiencies may still exist in the end-to-end processes as well as allow for better understanding of interfaces for partnerships and solicitations.

ISRU in Human Exploration

In-Situ Resource Utilization (ISRU) involves any hardware or operation that harnesses and utilizes local or in-situ resources to create products and services for robotic, and human exploration and sustained presence, instead of bringing them from Earth. The immediate goal of ISRU is to greatly reduce the direct expense of humans going to and returning from the Moon and Mars, to build toward the self-sufficiency of long-duration crewed space bases used to expand science and exploration efforts, and to enable the commercialization of space. To achieve the greatest benefits of ISRU incorporation into mission architectures, other systems need to be designed around the availability and use of ISRU-derived products. Therefore, ISRU is a disruptive capability and requires an architecture-level integrated system design approach from the start. The most significant impact ISRU has on missions and architectures is the ability to reduce launch mass, thereby reducing the size and/or number of the launch vehicles needed, or use the mass savings to allow other science and exploration hardware to be flown on the same launch vehicle. From past studies and analyses, somewhere between 7.5 and 13.1 kilograms of propellant and rocket stages are needed to deliver every 1 kilogram to the lunar or Martian surface. Therefore, the highest impact ISRU products that can be used early in human lunar operations are mission consumables including propellants, fuel cell reactants, and life support commodities.

Human Mars Surface Exploration

As was mentioned at the beginning of the section, Tables 6a, b, c, & d define a Mars human exploration architecture with a similar phased approach as being used for the Moon: Preparatory Missions, Pre-Outpost ("Boots on Mars"), Outpost Start ("build-up to sustainability"), and Sustained Presence. As with the human lunar exploration architecture, the Preparatory Phase has already started with several missions recently arriving on Mars and more orbiters and robotic landers planned for further science and resource understanding, in particular, understanding the "water cycle" and location, type, and amounts of surface and subsurface water and ice. Plans for the Pre-Outpost Phase vary from short duration stays on the Mars surface (30 to 90 days) to potentially 540 type day missions for Conjunction-class trajectories. For this phase, ISRU insertion will be based on enhancing mission capabilities or enabling mission capabilities if the mission need outweighs the risk. A major issue for the first crewed surface missions is the crew ascent vehicle mass, and particularly the delivery of the amount of propellant needed for ascent. It is anticipated that at a minimum ISRU oxygen production (e.g. derived from the Martian CO_2 atmosphere) for crew assent vehicle propulsion, and support and enhance life support oxygen/buffer gases for the habitat and EVA will be utilized. Some demonstrations, and utilization of manufacturing and construction capabilities, most likely with Earth-supplied feedstock, will be performed as well to minimize risks for future missions. During the Outpost Start Phase, it is anticipated that the type, scale, and range of products for ISRU will increase. If water mining and processing and methane production wasn't performed during the Pre-Outpost Phase, then it is anticipated that it will occur during this phase. ISRU demonstrations will be performed for full incorporation during the Sustained Presence phase. The Sustained Presence Phase will allow crew to stay for longer periods than a single Earth-Mars orbital alignment and begin to significantly reduce dependence on Earth and allowing infrastructure expansion.

Resource-Product-Application Assessment

The subject of ISRU covers a wide range of potential resources, products from these resources, and how these resources could be utilized in human exploration plans. The ISRU Gap Study team recognized early that not every option can be developed, that some might have a greater influence on mission cost and success than others, and that some might be needed earlier than others. In an attempt to trace how a potential resource could produce a possibly important product and how this product could potentially enhance or enable a mission-critical application or use, the team initially created two separate tables: a Resource vs. Product Table and a Product vs. User/Application table. For each table, the team attempted to assess both the impact the confluence might have on the architecture (high, medium, low, or not applicable) and when the human lunar exploration architecture might provide significant benefits (near-term, mid-term, or low-term). After each table was created, it was determined that integrating the two separate tables into one (Table 7) would provide decision-makers and developers a concise way to best understand this complex three-dimensional dependency, influence, and impact of potential resources to the applications that would utilize the products derived from these resources. From this activity, the team determined that the highest impact ISRU products that can be used early in human lunar operations are mission consumables including propellants, fuel cell reactants, life support commodities (such as water, oxygen, and buffer gases) from polar resources (highland regolith and water/volatiles in PSRs). While not in the original scope of the study, evaluation of human Mars architecture studies and Table 7 suggest that there can be significant synergy between Moon and Mars ISRU with respect to water and mineral resources of interest, products and usage, and phasing into mission architectures.

Technology, Facility, and Simulant Portfolio

To assess the state of ISRU development and identify where more work is needed, the ISRU Gap Assessment team performed a comprehensive assessment of past and recent efforts to develop ISRU technologies, systems, and capabilities as well as the facilities and simulants that are needed to prepare these ISRU efforts for flight. The technology assessment utilized the functional breakdown structure previously discussed. A table (Table 8) is included in the report which includes information on a portfolio of capabilities and developments for each function/subfunction and past/recent efforts from the participating countries/government agencies in each of these areas. This table highlights that a significant amount of work is underway or planned for ISRU development across all the countries/agencies involved in the study, particularly in the areas of resource assessment, robotics/mobility, and oxygen extraction from regolith.

The team recognized that to prepare ISRU for flight and future incorporation into human space exploration activities, the technologies, systems, and capabilities will need to be extensively tested on Earth under as realistic conditions as possible. Since lunar resources of interest are in or bound to lunar regolith, ISRU development requires facilities that can simulant lunar vacuum and temperature conditions while also allowing for hardware to interact with and/or process lunar regolith simulants. Facilities with these capabilities are unique since once regolith has been added to a vacuum chamber, it will most likely not meet the cleanliness levels required for most other system flight hardware verification and acceptance testing. Therefore, the team performed an assessment to determine what 1) facilities currently exist (or are in development/planned), 2) what environmental simulation capabilities they cover, and 3) what size of hardware can they accommodate that can support ISRU environmental testing. Table 9 in the report provides information on the status and capabilities of each country's/government agency's environmental facility capabilities. While engineered ambient test facilities were included in this assessment, natural analogue test locations were not. While it appears that each country/space agency has access to research and component/subsystem size test facilities that can accommodate regolith/dust and lunar vacuum/temperatures, there are a limited number of large system-level facilities that exist or are planned.

Lessons learned from hardware operation on early robotic and human exploration missions to the Moon showed that the success or failure of the hardware was greatly influenced by the simulant used to mimic lunar regolith in pre-flight testing. As knowledge of lunar regolith has increased, the ability to adequately replicate important aspects and characteristics of lunar regolith has increased, thereby increasing the likelihood of successful operation. Unlike other surface hardware and systems that try to avoid or mitigate interaction with lunar regolith, ISRU hardware and systems must interact with regolith on a continuous basis over months and years of operation. To successfully develop ISRU capabilities, it is recognized that a large amount of lunar regolith simulant will be needed and that different characteristics of the regolith will be important depending on the processes and technology being developed. For this reason, the ISRU Gap Assessment team performed an assessment of the state of existing Moon and Mars simulants as well as the potential availability for on-going and planned development efforts. Table 10 in the report provides a top-level understanding of Moon/Mars simulants for each country/government agency involved in the study. The assessment of simulants shows that 1) while simulants are available for development and testing, greater quantities and higher fidelity simulants will be needed soon, especially for polar/highland-type regolith, and 2) selection and use of proper simulants is critical for minimizing risks in development and flight operations.

It should be recognized that while the technology, facility, and simulant assessments were as comprehensive as possible, the inputs may not be all-inclusive. Therefore, sections were added to allow each country/government agency to provide further information about their specific activities and plans for ISRU development.

Gap Assessment

As the name implies, the ISRU Gap Assessment team was chartered to assess the state of the art for ISRU technologies, systems, and capabilities, and to define the remaining work (gaps) that will need to be performed and completed to finally achieve the desired end-goals for ISRU incorporation into human lunar and Mars exploration. To perform this task, the team utilized the highest priority/impact ISRU products and applications,

the ISRU functional breakdowns, and information gathered in the Technology Assessment to provide decision-makers and developers an understanding of the remaining work that needs to be addressed in future efforts. Because there are no firm requirements for ISRU products and systems, the gap assessment performed is meant to provide general information at the capability-level versus highly specific parameters that would be needed for a technology-level gap assessment. The reader is highly encouraged to examine closely the information provided in Table 8 since the table provides the greatest amount of information possible for technologies under consideration by each country/government agency. The reader is also encouraged to examine the mission phasing and priority/impacts for ISRU demonstrations and systems in Table 5a, b, and c Human Lunar Exploration -Phases, and Table 7 ISRU Resources, Products, and Applications to better understand the overall importance of closing different technology and capability gaps.
The following specific gap assessments were performed and a high-level summary is provided hereafter.

Destination, Reconnaissance, and Resource Assessment
A major objective for human lunar and Mars exploration is to be able to acquire and utilize in-situ resources to enable sustained surface operations and future commercialization of space. To achieve this objective, detailed knowledge of the location, type, and distribution of potential resources is needed to select outpost and mining locations, and develop technologies and systems to extract and process the resources. Therefore, the knowledge in the destination, reconnaissance and resource assessment, critical technologies, and data collection-management need to have crucial roles early in human lunar and Mars exploration plans. While information from Apollo missions and regolith samples and orbital science missions have provided excellent information on regolith properties and global understanding of resources, knowledge about polar regolith and resources, especially in Permanently Shadowed Regions (PSRs), is currently insufficient to eliminate or mitigate risk in site selection and mining technology development. The team assessment identified new efforts in refocusing technologies and instrumentation for lunar and Mars operations, and several missions to begin surface and deep assessment of resources are in development, especially to obtain maps of minerals on the lunar surface, surface topography and terrain features, or to understand the depth profile of water and volatiles. Almost all space agencies are working on instruments for physical/geotechnical and mineral/chemistry characterization of regolith. There is also strong interest in developing instruments and hardware for subsurface ice indirect and direct characterization. There is also strong interest in developing mobile resource exploration and autonomy.

While work on resource assessment physical, mineral, and water/volatile measurement instruments are underway, and new orbital and lunar surface missions are in development or planned, a focused and coordinated lunar resource assessment effort is needed. Resources characterization determines the interest to use instrumentation with specific performances, and in general, instrumentations with higher performances can be of help to better plan resource assessment and mining operations as well as potentially support direct landing within PSRs. Determine these constraints is basilar to support new efforts in refocusing technologies and instrumentation for lunar or Mars operations, several missions to begin surface and deep assessment of resources are in development, especially to obtain maps of minerals on the lunar surface, surface topography, and terrain features, or to understand the depth profile of water and volatiles.

Resource Acquisition, Isolation and Preparation
Once a resource has been identified, located, and characterized, the next step in achieving a product from the resource is the ability to extract/acquire, separate, and potentially prepare the gas or material for processing. Requirements for resource acquisition, isolation, and preparation are linked to resource processing techniques. Technological challenges are linked to needs of resources acquisition, isolation, and preparation: long duration and high level of performances as excavate and analyse raw materials contents require optimized machines. The presence of contaminants from the extracted gas resources or accumulation of contaminants in regenerative chemical processing represents critical problems that need reliable solutions. Mobility operations, locomotion, and storage of tons of raw materials require an integrated plan of management and optimization. Robotic systems need to be able to work in hard conditions as in dusty environments and need to be endowed of Autonomy and localization systems through the appropriate integration of AI, sensors, and Communication & Navigation instruments. Some advanced technologies for the direct collection of gasses from Mars atmosphere

and excavation of lunar regolith are already under development. There is strong interest in developing hardware for sample excavation of granular and hard/icy regolith. There is currently limited work on crushing, size sorting, and mineral beneficiation, most likely due to lack of firm requirements.

Resource Processing for Production of Mission Consumables

Through evaluation of potential resources, products, and applications for lunar exploration, the primary processes and products of interest are oxygen extracted from regolith and ice extracted from polar permanently shadowed regions. To achieve implementation of these processes/products into future missions, relevant environment simulating Moon and Mars environment conditions need to be used to demonstrate autonomous operations and multi-step processing: physical and chemical processes are well defined, these techniques require significant advancement before the incorporation into a mission demonstrator. Storage and managing systems for potential volatiles need to be validated also in Moon and Mars environmental conditions. The assessment performed identified complementary and overlapping work on oxygen extraction and limited work on water extraction, mostly at demonstration scale. Water and carbon dioxide processing technologies for the Moon and Mars were mostly related to life support or terrestrial applications.

Resource Processing for Production of Manufacturing and Construction Feedstock

Bulk or refined regolith will be the main constituent for construction, and manufacturing until more refined feedstock is available. Regolith is also at the base of ISRU processing to extract useful gasses and water but also metals, which require complex reactant regeneration and metal separation steps in vacuum. Metal extraction processes requires generally also large amounts of power, necessary for both molten regolith electrolysis and molten salt electrolysis technologies. Resource processing to produce plastics typically require complex and multi-step methods, and also silicon production requires specific processes that need to be demonstrated for space applications. As with oxygen extraction from regolith, complementary and overlapping work exists on metal extraction at the demonstration scale, and most of the work is in the US and Europe.

Civil Engineering and Surface Construction

To make site habitable and functional starting from a site characterized by complex shape terrains requires the detailed evaluation of the natural shape, the soil characteristics, atmospheric conditions and winds (as in the Mars case), solar exposure conditions. Distances and road practicability from the relevant raw materials and establishment and maintenance of resource sites are also key factors. Regolith shielding is a possible idea for habitats but all the related elements to make them habitable are not simple: architecture design needs to address all the constraints imposed by the habitability and ISRU facilities. A significant radiation shielding needs to be realized for long, sustained human surface exploration activities. Long-term (months/years) radiation exposure limits for crew currently do not exist to properly evaluate radiation shielding requirements. These are needed to properly evaluate Earth-based and ISRU-based shielding options. Specific manufacturing methods can be used as additive manufacturing that present relevant performance and a flexible approach but may limit the architectural opportunities. Brickmaking may represent another functional method for the realization of specific architectural sections and, at the moment, an appropriate combination of these two techniques needs to be developed to reduce their limits. While there is significant interest in terrestrial additive manufacturing/construction development, development for space applications has been limited and primarily under Earth-ambient conditions. Most of the current work is focused in US and Europe, with an emphasis currently on additive manufacturing approaches.

In-Space Manufacturing

Some relevant technics used for In-Space Manufacturing for ISRU are using regolith with selective laser sintering method or stereolithography-based additive manufacturing. These technologies are under development or are already demonstrated but only in terrestrial laboratory, and techniques need to be verified in reduced gravity condition, as on the International Space Station (ISS). Metals and polymers additive manufacturing techniques have been implemented or are being developed also for application in microgravity, on the ISS. Also, subtractive manufacturing systems are currently being developed for the ISS. Application for ISRU-derived feedstock should be investigated for Moon and Mars missions. Process monitoring and part verification is a key field of activity for in-space manufacturing applications. Similarly, all the techniques and methodologies enabling the possibility to recycle ISRU-derived manufactured parts should continue to be investigated, as well as the impact of multiple recycling of the parts' properties and material processability.

ISRU Flight Missions Planning

As with any new technology, before it can be utilized in a mission critical role for human spaceflight, it needs to undergo significant ground development and adequately demonstrate its life and performance in the actual mission environment. In the report, the ISRU Gap Assessment team outlines a phased development and flight strategy to increase confidence and decrease risk in the technologies and systems required to provide useful products in a mission-critical application. The approach for risk reduction of including ISRU elements in the surface exploration architecture may ultimately come down to the potential customers. Sufficient level of confidence to fly ground demonstrated systems or to undertake intermediate technology demonstration steps in advance of operational systems should be defined by the relevant users.

While a new international human lunar architecture is still in work, it should be noted that individual nations and space agencies are progressing with plans for new lunar orbital and surface missions. Many of these missions, as highlighted in Table 11 *Approved and Planned ISRU-Related Flight Missions* are in planning or already underway for flight this decade.

Partnerships and Private Sector Involvement

Partnerships are a well-established means of delivering more significant mission outcomes than could otherwise be achieved by a single agency or organisation. Therefore, a key benefit is to expand inter-agency collaboration, between space agencies and also with other key government agencies, to address the ISRU gaps outlined in this report while providing socio-economic benefits on Earth. A strategic approach to expanding collaboration can encompass the following key activities: coordinated planning; shared knowledge and insights; harmonisation of research agendas; specific joint-development projects for ISRU systems; and access to shared test facilities.

More recently, the role of the private sector has evolved across a vast range of space operations and is expected to have an even greater impact on the field of ISRU. To fully benefit from further commercial involvement, this report highlights a strategic approach to leveraging the capabilities of the private sector, including both new start-ups and from mature terrestrial industries such as the global mining, civil construction, resource, and manufacturing sectors. To realize the goals of ISRU, there is a need to recognize the benefits of adapting mature and modern terrestrial industry capabilities to advance space operations. At the same time, the application of newly-developed ISRU technologies can also deliver enhanced solutions for productivity gains and address common challenges (e.g. working in harsh, hazardous, and remote environments) for terrestrial industries.

BACKGROUND

In-Situ Resource Utilisation (ISRU) is the use of natural resources from the Moon, Mars, and other bodies for use in-situ or elsewhere in the Solar System. A second level of ISRU can be the reuse/recycling of waste materials and repurposing of equipment for new applications. The implementation of ISRU technologies is thought to provide a breakthrough in science and strong leverage for humankind to explore further into space.

Due to the launch cost of interplanetary travel and especially to planetary surfaces, sustainable exploration activities may be achieved through ISRU for resources that are available locally instead of transporting them from Earth. Examples of areas of application are propulsion, energy storage, life support, radiation protection, and waste management. For example, water can be electrolysed to serve as propellant or fuel/reactant for energy storage systems, but also be of direct use for crew as a life-support consumable. The lunar regolith itself can be used to extract metals and other materials for in-situ manufacturing of hardware and construction of landing and habitation structures, by means of additive manufacturing or/and with the help of astronauts.

The Moon represents a critical location for the expansion of humanity beyond Low Earth Orbit (LEO), to Mars and into the Solar System. The initial Phases will be dedicated to the conversion of local resources into useful products, involving extensive lunar industries. These industries may include raw material processing, oxygen and other propellant production, solar power and energy storage, and the creation of new space vehicles. For protection against radiation, lunar bases may include shielding structures or/and underground habitats. Solar system exploration using in-situ resource utilisation can allow broader and more effective in-situ research by astronauts as well as faster implementation of sample return missions.

The ISRU value chain can be enclosed in a simplified five-stage process flowsheet: Find, Excavate, Refine, Extract, and Supply Product. All these steps need to be considered concurrently for a successful implementation of space resources utilisation. The following is a more comprehensive description of the value chain for ISRU:

- Prospect: Following the identification of potential resources, the characterisation of feedstock properties and knowledge of the lunar or planetary geology takes place, including mineralogy, physical characteristics, and the variability in local materials.
- Establish/Settle: Once areas of rich resources are characterised and mapped accordingly, these can be established as landing spots for large-scale operations and settlement.
- Mine (Excavation): Excavation, hauling, and handling regolith feedstocks prior to processing.
- Transport: The transfer of material from the excavation system to the processing system is a key element since different beneficiation and extraction systems will require specific transportation capabilities.
- Refine/Prepare (Beneficiation): Physical or chemical beneficiation increases the mass fraction of the component of interest in the feedstock by removing other components that are less useful or may interfere with the subsequent extraction.
- Produce (Extraction): Chemical reduction process (or others) to manufacture products of interest, e.g. oxygen and metal alloys, from lunar materials.
- Supply: Product storage and (standard) interfaces for transfer and handover of the products to subsequent processing steps, and ultimately to the final users. Subsequent processing steps can include product purification according to the requirements of the final user (e.g. water and gas purification to remove dust particles, sulphides, and other impurities). Supply products to applications of interest (e.g. propulsion, energy storage, life-support, manufacturing, and construction).

STUDY GOALS AND OBJECTIVES

The International Space Exploration Coordination Group (ISECG) is a forum where space agencies/offices work collectively in a non-binding, consensus-driven manner towards advancing the Global Exploration Strategy. The ISECG 2018 Global Exploration Roadmap (GER) captures the shared vision for international collaboration in space exploration based upon a common set of exploration goals, objectives, and identified benefits to humanity. It reflects an exploration strategy for the International Space Station (ISS) and extending to the Moon and its vicinity, asteroids, Mars, and other destinations.

A supplement to the GER has been recently published in August 2020 to include an extension and refinement of the ISECG reference Lunar Surface Exploration Scenario. Among these updates, a set of dedicated Lunar Surface Exploration Scenario Objectives was developed. This set of objectives is based on the principle that human Moon surface exploration should focus on the preparation for human Mars missions and for sustainable activities on the Moon leveraging ISRU. The updated Lunar Surface Exploration Scenario implements a phased approach and follows the sustainability principles from the 2018 GER: Phase 1 - Boots on the Moon; Phase 2 - Expanding and Building (Longer Duration and Increased Utilisation); Phase 3 - Sustained Lunar Opportunities.

The Technology Working Group (TWG) is one of the working teams of the ISECG. The principal goal of the TWG is to facilitate leveraging investments in technology development efforts of individual ISECG agencies supporting the implementation of the GER and to advocate coordination and collaboration in technology development efforts of individual ISECG space agencies in support of the GER mission scenario. In order to assess what are the critical technology gaps to fulfil the architecture requirements in the scope of the GER. The TWG delivers new and updated products on a regular basis, such as this specific technology gap assessment report.

In 2019, the TWG has established a Gap Assessment Team (GAT) for the topic of ISRU. The ISRU GAT was created to address the identified technology needs and inform the ISECG on technology gaps that must be addressed in order to implement the foreseen missions. Ultimately, this initiative intended to create international dialogue among experts and inform agency decisions when considering investments in specific exploration technologies, while identifying potential collaboration opportunities.

The ISRU-GAT study goals and objectives laid emphasis on the following questions:

- What could the international community do to advance ISRU utilization as quickly as possible?
- How can current GER elements and architectures be adapted so that they are ready to use ISRU products?
- What specific technology areas are seen as drivers to be considered by Agencies in support of follow-on commercial involvement?

The following key objectives were considered as a starting point:

- Enable ISRU products for Construction, Life Support, and Propulsion systems (e.g. materials, oxygen, propellants)
- Examine adapting the Exploration architecture to start with Earth provided products but allow for ISRU-based products to be part of system design and certification (e.g. refilling/refuelling)
- Consider missions post-ISRU certification to be centrally distributed (hub-and-spoke) vs separate standalone lunar surface missions

APPROACH

The approach used at the start of this study was defined in terms of initial goals and methodology to follow. The identification of key tasks and questions was put forward:

- Review existing portfolio entries (as per currently elements/capabilities tied to the GER architecture);
- Identify what updates are needed (if any) to the current portfolio of technologies to reflect the respective agency activities/interest related to the GER;
- What are the gaps for the identified technologies and capabilities, initially focusing on critical technologies;
- What are the key technologies/engineering solutions for closing the identified gaps;
- Identify potential partnership/collaboration opportunities at agency level.

Predominantly, and based on the existing plans to return astronauts to the surface of the Moon, the focus of this document is on lunar ISRU with intended potential forward capability towards the Mars context. The following tasks and scope of the document aim to answer the needs for early exploration and preparation for sustainable human presence on the Moon. Mars ISRU considerations are touched upon very briefly, with the scoping of potential Mars ISRU scenarios that lead to the identification of foreseen resources, products, and applications. Following the same approach for Moon and Mars, to identify relevant ISRU-related capabilities, a portfolio of agency-wide activities in the areas of simulants, test facilities, and technologies was elaborated.

The ISRU GAT took upon investigating what are the gaps for the relevant technologies and capabilities, as well as identifying key technology/engineering solutions for closing the gaps. This exercise included (non-exhaustive list):

- Review of ground rules, assumptions, and objectives for the lunar ISRU scenarios in support of human exploration;
- Evaluate Strategic Knowledge Gaps and applicability/importance to ISRU development and utilisation;
- Categorise ISRU Resources vs Products vs Users/Applications as a function of impact and insertion timeline on potential mission scenarios;
- Define an ISRU functional flowchart and work/technology breakdown structure;
- Survey ISRU technologies/system capability in each agency while highlighting and substantiating the gaps;
- Identify worldwide existing test facilities and regolith simulants necessary to develop ISRU technologies and systems before flight.

It was considered that each space agency might have specific funding constraints and a national strategy that defines the type, variety, and pace of technology development in support of future exploration missions. Therefore, it was judged important to coordinate capabilities among international agencies in order to focus on specific critical areas and guide national efforts.

IN-SITU RESOURCE UTILIZATION (ISRU) OVERVIEW

What is In-Situ Resource Utilization (ISRU)?

In-Situ Resource Utilization (ISRU) involves any hardware or operation that harnesses and utilizes local or in-situ resources to create products and services for robotic, and human exploration and sustained presence. Local resources include ‘natural’ resources found on extraterrestrial bodies such as water, solar wind implanted volatiles (hydrogen, helium, carbon, nitrogen, etc.), vast quantities of metals in mineral rocks and soils, and atmospheric constituents, as well as human-made resources such as trash and waste from human crew, and discarded hardware that has completed its primary purpose. The incorporation of ISRU systems and capabilities that can harness and utilize resources found at the site of exploration, instead of bringing everything from Earth, cover a wide range of potential applications, technologies, and technical disciplines. ISRU covers three broad areas depicted in Figure 1; In-Situ Propellant & Consumable Production, In-Situ Construction, and In-Space Manufacturing with ISRU-Derived Feedstock. These three broad areas will be covered in more detail in the Taxonomy section.

The immediate goal of ISRU is to greatly reduce the direct expense of humans going to and returning from the Moon and Mars, and then to build toward the self-sufficiency of long-duration crewed space bases used to expand science and exploration efforts, and to enable the commercialization of space. To achieve the greatest benefits of ISRU incorporation into mission architectures, other systems need to be designed around the availability and use of ISRU-derived products. Therefore, ISRU is a disruptive capability and requires an architecture-level integrated system design approach from the start. To minimize infrastructure mass and achieve the greatest return on investment, lunar ISRU systems must operate for extremely long periods of time (most of the time without crew), in harsh environments, and with extremely abrasive lunar regolith/extraterrestrial soils. When considering the communication delays between Earth and Mars, ISRU systems also need to operate autonomously with minimal human supervision.

The most useful mission consumable products from ISRU are propellants, fuel cell reactants, life support commodities (such as water, oxygen, and buffer gases). Since propellants make up a significant mass fraction of space transportation and lander/ascent vehicles, making propellants or even oxygen alone can provide significant mission savings, and lead to more sustainable and reusable space transportation systems. The ability to provide radiation shielding for crew through use of in-situ derived materials, and protection of surface infrastructure from landing/ascent plume debris and micrometeoroid impacts through civil engineering and in-situ construction are also extremely important for sustained human lunar surface exploration.

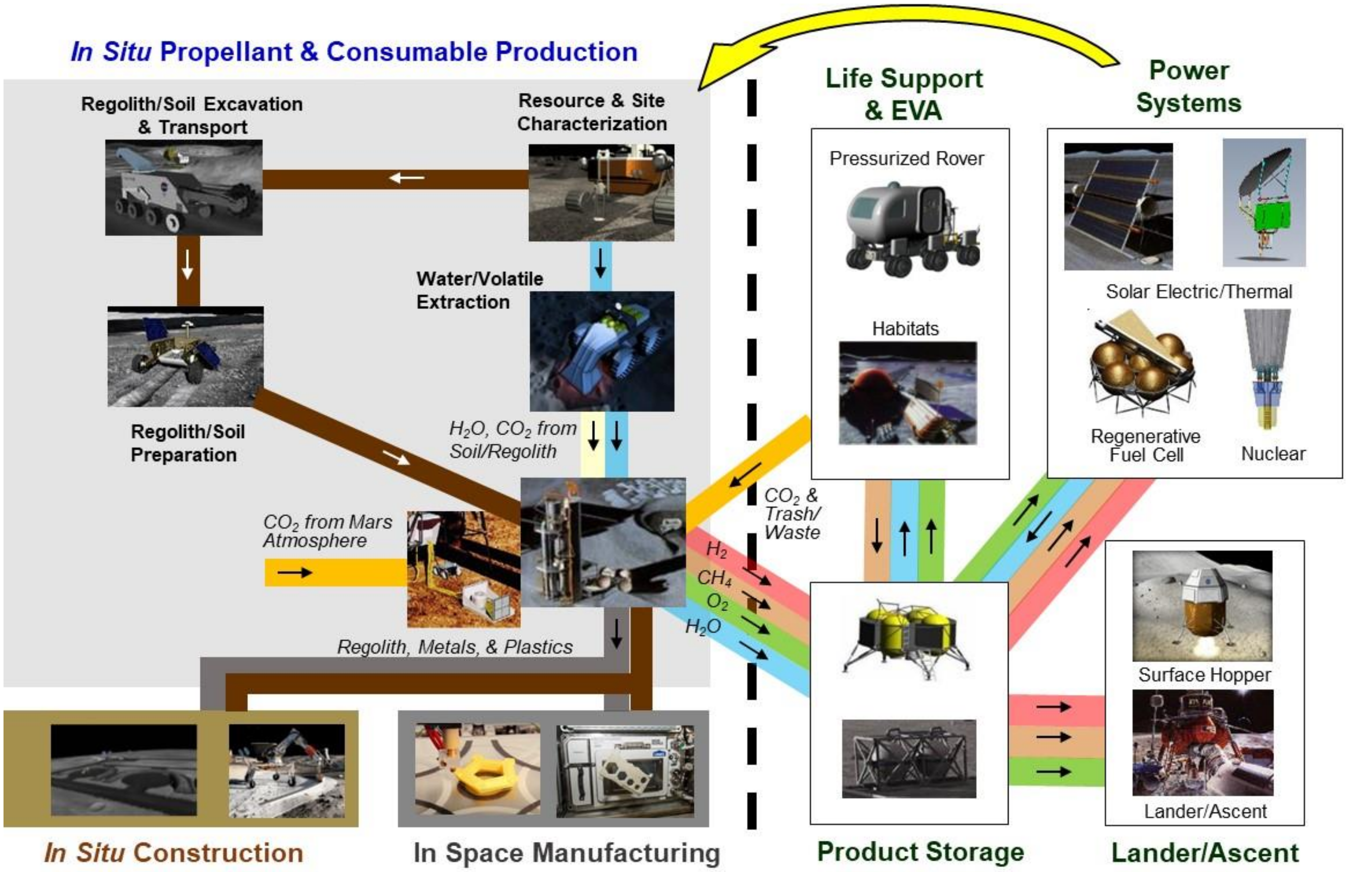


Figure 1. In-Situ Resource Utilization (ISRU) and Connections to Surface Systems

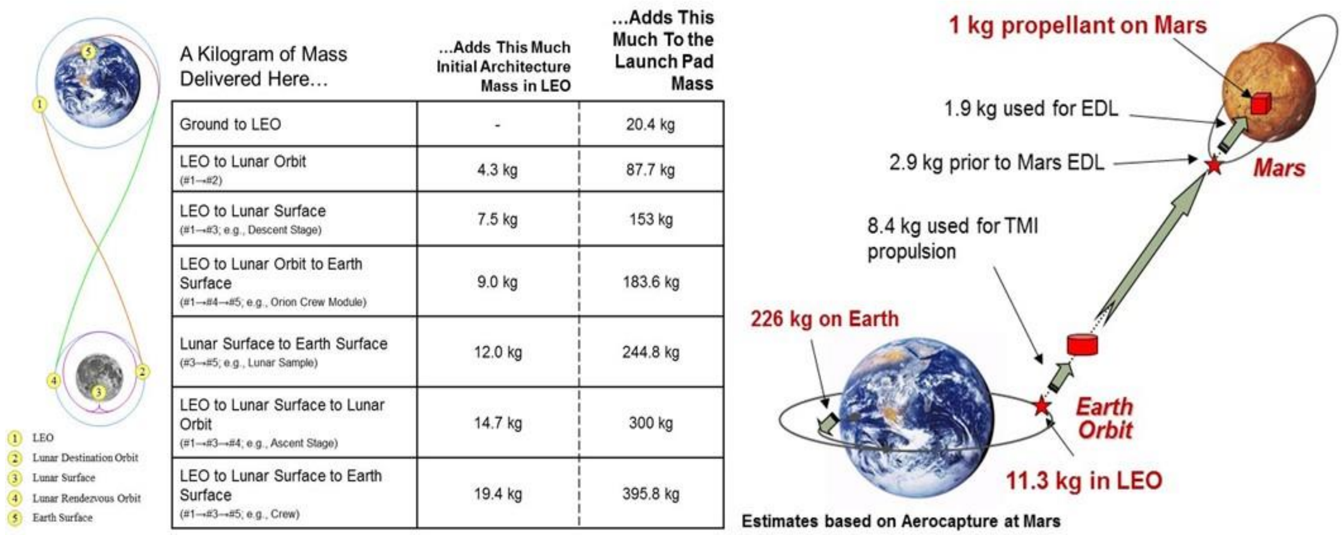
ISRU Mission and Architectures Impacts and Benefits

ISRU is a disruptive capability for missions and architectures. Incorporation of ISRU can enable more affordable exploration than today's paradigm of taking everything from Earth. While ISRU can allow a more sustainable architecture to be developed, it also requires an architecture-level integrated system design approach. This is because ISRU products can influence transportation and other surface elements/capability development, and ISRU systems require resources and capabilities from other surface elements/capabilities. Some of the main impacts and benefits of ISRU incorporation into human mission and architecture plans include:

- **Launch mass savings**: propellants, life support, consumables, space radiation shielding, parts for repairs, and new hardware
- **Reduce launch numbers**: risk/cost reduction. logistics reduction
- **Mission life extensions**: local supply of critical consumables without waiting for new Earth supply, repairs with local materials, repurposing of end-of-life hardware
- **Provide critical solutions for mission assurance**: safe landing zones preparation, extra propellant for return to Earth (leakage/storage failure), large-scale surface shielding, and shelter from space radiation and weather (dust storms, temperature extremes, etc.)
- **Ensure crew safety**: dissimilar redundancy for life support consumables, repairs, radiation shielding, increased independence from Earth logistics
- **Relax critical requirements**: propulsion performance (Isp) and complexity (ex. press-fed vs pump-fed), amount of closure of life support (ex. efficiency of water removal from brine)
- **Enable mission capabilities not possible or difficult without ISRU**: reusable landers and space transportation, surface hoppers with ISRU propellant, hydrocarbon-based fuel cells for surface mobility, and trash disposal (propellants and planetary protection)

- **Space commercialization**: Develop technology, create markets, and reduce risk for space commercialization

The most significant impact ISRU has on missions and architectures is the ability to reduce launch mass, thereby reducing the size and/or number of the launch vehicles needed, or use the mass savings to allow other science and exploration hardware to be flown on the same launch vehicle. The mass savings from not requiring everything needed to successfully complete a mission or build up an architecture from Earth comes from what is known as the 'Gear Ratio' effect. The Gear Ratio effect is based on the fact that for every kilogram of anything (hardware, consumables, crew, etc.) landed on a planetary surface like the Moon, multiple rocket stages and propellants are needed to deliver that kilogram of payload to the surface destination. From past studies and analyses (see Figure 2), somewhere between 7.5 and 13.1 kilograms of propellant and rocket stages are needed to deliver every 1 kilogram to the lunar or Martian surface. Because of this, production of propellants for Moon/Mars ascent vehicles and reusing hoppers and landers is the main initial focus of ISRU development and implementation. When considering that it can take 5 to 10 metric tons of propellant to ascend from the lunar surface to the Gateway, 25 to 30 metric tons of propellant to ascend from the Mars surface to high Mars orbit, and 40 to 50 metric tons of propellant for a reusable lunar ascent/descent lander, multiplying these amounts of propellant (per mission) by the Gear Ratio (7.5 to 13.1) results in a significant amount of launch mass reduction or number of launch vehicles needed over the life of an architecture.



A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew)	19.4 kg	395.8 kg

Figure 2. Gear Ratio of Mass Delivered by Starting Location

Lunar Resources

In-situ resources can encompass natural resources, as well as man-made resources such as crew waste and trash, discarded landers and tanks, and anything brought from Earth that has completed its nominal mission use. From a natural resource perspective, the Moon has a vast variety of mineral and volatile resources. For simplicity, the resources can be divided into two broad categories: lunar regolith-based and polar water/volatile-based. This section of the report is meant to provide a general understanding of resources on the Moon and the reader is advised to examine the Lunar Sourcebook, New Views of the Moon, and other newer references for more detailed information.

Lunar regolith-based resources include the bulk regolith itself as well as specific constituents that might be of interest such as pyroclastic glass and KREEP (potassium, rare earth elements, phosphorous) deposits and solar wind implanted volatiles. Bulk lunar regolith can be further divided into two broad categories: Mare and Highland. Lunar mare (the dark black areas on the Moon) is basaltic and made up primarily of plagioclase feldspar, pyroxene, and olivine, with varying amounts of ilmenite and other constituents. Ilmenite is a titanium-iron oxide that can be reduced more easily than other minerals and can vary in content from approximately 5 to 15% of lunar mare regolith. Highland regolith is magmatic and primarily consists of plagioclase (mainly anorthite, the calcium-rich end-member) with smaller amounts of pyroxene and olivine. Two important factors to consider about lunar regolith is that it contains over 40% oxygen by mass and is primarily made up of silicate minerals (up to 90% or more). Lunar regolith also contains a large fraction of agglutinitic glass which is made up of fused and partially melted regolith minerals. KREEP rocks are crystalline highland rocks that contain a chemical component enriched in such elements as potassium (K), rare-earth elements (REE), and phosphorus (P). Regolith with KREEP usually also includes relatively higher concentrations for radioactive uranium and thorium. KREEP material may be of interest for future commercial metal extraction operations.

Solar wind volatiles are elements that constantly bombard the lunar surface from the Sun's solar wind and coronal ejections. The solar wind includes hydrogen (H), helium (He), carbon (C), nitrogen (N), fluorine (F), and chlorine (Cl) elements, and can be found in higher concentrations in agglutinates and pyroclastic glass. The amount of solar wind elements in regolith, agglutinates, and pyroclastic glasses varies from as low as 3 parts per million (ppm) to over 200 ppm depending on the material and the element (see Table 1). Helium is found in both isotopes of helium-4 and helium-3, but helium-3 is only found in parts per billion (ppb) so significant amounts of regolith would need to be processed to obtain any appreciable amount. Solar wind volatiles are the only sources of hydrogen and carbon on the Moon outside of the Permanently Shadowed Regions (PSRs).

Table 1. Solar Wind Volatiles [1]

Volatile	Concentration ppm (μg/g)	Average mass per m^3 of regolith (g)
H	46 ± 16	76
^{3}He	0.0042 ± 0.0034	0.007
^{4}He	14.0 ± 11.3	23
C	124 ± 45	206
N	81 ± 37	135
F	70 ± 47	116
Cl	30 ± 20	50

The most interesting but least known resource on the Moon is water and other volatiles that exist in permanently shadowed regions at the lunar poles. While the Moon was once thought to be bone dry after regolith samples from Apollo missions were sampled on Earth, that view has steadily changed ever since the Clementine and Lunar Prospector missions found evidence that water ice might exist in lunar PSRs. Subsequent missions, especially the Lunar Reconnaissance Orbiter (LRO), the Moon-Mineral Mapper (M^3) instrument on Chandrayaan, and the Lunar CRater Observation and Sensing Satellite (LCROSS) have provided more information and evidence of water and other volatiles in PSRs. However, there is only one 'ground truth' measurement to date of these resources, and that is the LCROSS impact (Table 2). Estimates of water content vary from the LCROSS 5.5 weight percent (wt%) water +/- 2.9% (Colaprete) to up to 30 wt% water (Li et al 2018).

Table 2. LCROSS Plume Volatile Estimates [2]

Molecule	%wt	Molecule	%wt	Molecule	%wt
Water: H_2O	5.5	Calcium: Ca	0.20	Carbon Monoxide: CO	0.70
Hydrogen: H_2	1.40	Mercury: Hg	0.24	Ethylene: C_2H_4	0.27
Hydrogen Sulfide: H_2S	1.74	Magnesium: Mg	0.40	Carbon Dioxide: CO_2	0.32
Ammonia: NH_3	0.31	Sodium: Na	-	Methanol: CH_3OH	0.15
Hydroxyl: OH	0.00	Sulfur Dioxide: SO_2	0.64	Methane: CH_4	0.03

Lunar regolith as raw material for building has been investigated regarding binder-based as well as direct-sintering techniques. Mechanical strengths comparable to regular concrete can in principle be achieved with regolith as the main ingredient. While bulk processes such as brick making are relatively robust, 3D-printing processes require a delicate level of process control to deal with the materials' innate variabilities but have been demonstrated multiple times.

Mars Resources

The primary resource on Mars is its atmosphere. The Mars atmosphere is primarily made up of carbon dioxide: CO_2 (95.32 vol%), nitrogen: N_2 (2.7 vol%), and argon: Ar (1.6 vol%), with minor amounts of oxygen: O_2 (0.13 vol%), carbon monoxide: CO (0.08 vol%), and trace amounts of water: H_2O (210 ppm), nitric oxide: NO (180 ppm), and other elements. The pressure and temperature of the atmosphere varies as a function of altitude, latitude, season, and time of day. The surface pressure can range from 4 to 9 mbar (0.06 to 0.13 psi), and the temperature can range from 5 to -112 °C (41 to -170 °F).

An equally important resource on Mars is water, however, it is more difficult to acquire than the atmosphere since it requires excavation or drilling and material processing. From early Mars missions, especially the Viking lander soil processing experiment, it appeared that Mars was very dry until science data from the Mars Odyssey orbiter and subsequent robotic missions revealed that water may be widely accessible all across the surface of Mars. Neutron spectroscopy data from Mars Odyssey shows that water content varies from a low of <1 wt% to >10 wt% in the mid-latitude band of Mars (-30 to +30 latitude) in the upper 1 meter of Mars surface material. Other orbital instruments have located deposits of phyllosilicates, carbonates, sulfates, and silica bearing deposits in the same region that should contain enhanced water content from 6 to 10 wt%. Even the loose granular soil found across Mars is expected to contain 1 to 3 wt% water based on Viking I and II and Sample Analysis on Mars (SAM) instrument data from the Curiosity rover. From Mars orbital radar measurements (SHARAD and MARSIS), and from locating and imaging recently formed craters on the surface of Mars, more and more evidence suggests that vast subsurface ice deposits may exist near the Mars surface (top 10 m) in the mid to mid-upper latitudes (+/- 35 to 60 degrees). For Mars ISRU technology and system studies, three general Mars water sources are used to evaluate concept and mission benefits: 1) loose granular soil at the surface with 1.3 wt% water, 2) harder/consolidated hydrated minerals at 8 wt% water, and subsurface ice sheets at least a few meters below the surface in mid-upper latitude based on the Mars Water ISRU Measurement study report, SAM instrument data, and discussions with Mars scientists.

Regarding the utilization of regolith for building, a similar assessment as for the Moon applies. Temperature differences are less than on the Moon but can be up to 200K, hence they are beyond Earth requirements for building materials as well.

ISRU Strategic Knowledge Gaps (SKGs)

During NASA's Constellation human lunar exploration program, Dr. Michael Wargo, Chief Exploration Scientist for the Human Exploration and Operations Mission Directorate, led an effort to examine and define the information that was still needed about the Moon, exploration technologies and operations, and keeping humans alive and well in space to successfully achieve the goals and objectives of human lunar exploration. The main product of this effort was the creation of a list of Strategic Knowledge Gaps (or SKGs) that would be used to help guide and prioritize development and flight activities. The list of SKGs was presented to the members of the ISECG, and after review and modification was accepted as a product of the Global Exploration Roadmap (GER) for all the space agencies to use. The agreed-upon SKG document divided strategic knowledge gaps into three broad categories:

- Theme 1 – Understand the Lunar Resource Potential
- Theme 2 – Understand the Lunar Environment and its Effect on Human Life
- Theme 3 – Understand How to Work and Live on the Lunar Surface

In 2016, the Lunar Exploration Analysis Group (LEAG) was tasked by NASA to reexamine the ISECG SKG document to remove gaps that had been closed and update/modify gaps that still existed. The results of the

LEAG Special Action Team (SAT) review of the SKGs can be found at the NASA website (https://www.nasa.gov/exploration/library/skg.html).

The ISRU Gap Study team utilized the 2016 LEAG SAT SKG documents for Theme 1 and Theme 3 as a starting point to examine which SKGs were of particular importance to ISRU development and implementation. The SKGs defined in Theme 2 were not examined in this study or included in Table 3 since the team did believe they were relevant to ISRU.

To better inform how SKGs relate to ISRU, the team divided ISRU into 5 major categories based on critical ISRU functions and products that are discussed later in the report:

- Polar Water
- Solar Wind Volatiles
- Oxygen from Regolith
- Construction and Manufacturing
- ISRU Operations

The team then assessed what the priority of each SKG is with respect to the type of ISRU, and the phase in the human lunar architecture that it supports (as defined in the *Human Lunar Exploration Phases* section of the report). The ISRU-relevant SKGs were further assessed to determine where the knowledge gap will be closed (ground or flight) and whether the gap was a scientific or technology gap. Lastly, each SKG was linked to the ISRU Phase and Objective which would need and/or close the gap. Table 3a & b are the final product of the SKG assessment and provides a concise understanding of the SKG as it relates to ISRU area, priority, and impact to ISRU capabilities, and which mission Phase/ISRU objective the gap is tied to. Table 3b denotes the original LEAG SAT SKG theme and number. Please note that the ISRU Gap Study team identified two new SKGs (III.A.5 & .6) that need to be addressed that were not part of the original list.

Table 3. ISRU Strategic Knowledge Gaps

H = High Impact - Important for initial sustained operation at the lunar polar region (according to Artemis program) M = Medium Impact - Important for longer-term sustained operations or for non-polar regions L = Low Impact - Limited importance to area of ISRU; limited impact to the architecture	**ISRU Operations** - Definition: The SKG is applicable to all ISRU areas as well as potentially other surface activities., e.g. communication and navigation - Impact is assessed for each ISRU area. A single impact designation in the ISRU Ops column means all other colored columns have the same priority

Table 3. ISRU Strategic Knowledge Gaps

Polar Water (& polar volatiles)	Solar Wind Volatiles	O_2 from Regolith	Construction & Manufacturing	ISRU Ops	LEAG Designation	Strategic Knowledge Gap Title	Strategic Knowledge Gap Subelements	Categorization & Min. Gap Closure Approach	Architecture Integration
						I. Understanding the Lunar Resource Potential	**Breakdown/Narative**	**Science/Technology; Ground/Flight**	
						B. Regolith (Earth Testing)			
	L	M			1	Quality/quantity/distribution/form of H species and other volatiles in mare and highlands regolith. Apollo heritage (samples)	Measure volatiles and organics returned in "pristine" Apollo samples. Measure the extent of disruption of volatiles during handling and processing	Science/Ground	
	L	M					Measure volatiles and organics returned from new locations on the lunar surface, and measure the extent of disruption of volatiles during handling and processing. Utilize new technologies to minimize sample container leakage and oxidation of samples returned	Science/Ground	
						C. Regolith (Moon Volatiles- non PSR)	Multiple measurements of undisturbed soil at depth at meter and decameter scales (laterally) and 0-2m depth. Need to measure abundance of solar wind gases or H species at the 10 ppm level. Need capability for multiple analyses at different locales and subsurface depths		
	M				2	Quality/quantity/distribution/form of H species and other volatiles in mare and highlands regolith	Knowledge of hydrogen-resources in Mare and Highland regolith at non-polar locations: location, type, concentration in different minerals, energy to release	Science/Flight	S1.1, 1.2, 1.3, 1.4, 1.5, 1.8
	H						Knowledge of hydrogen-resources in non-PSR regolith at polar locations: location, type, concentration in different minerals, energy to release tied to physical/mineral characterization	Science/Flight	S1.1, S1.2, S1.3, S1.5, S1.8
	M						Measure volatiles and organics released from returned samples	Science/Flight & Ground	
	M						Losses of volatiles (solar wind deposited) in regolith during excavation and processing	Technology/Flt Demo	S1.2, S1.5
L	M				3	Preservation of volatile and organic components during robotic and crew sampling, handling, storage, and curation.	- The volatile record that is preserved in lunar regolith is very fragile and could be easily disturbed during sampling-analysis by robotic and human exploration of volatile polar and non-polar deposits. Methodologies and technologies must be developed to access, handle, contain, and curate these valuable samples to minimize volatile loss and contamination. - Requires creation and analysis of appropriate simulant materials and studies. Comparison of in-situ and new returned samples would definitively address this SKG	Science/Flight & Ground	S1.5
						D. Polar Resources - Partially & Permanently Shadowed Regions (PSRs)			
H					3	Geotechnical characteristics of cold traps	Requires ground truth at the 10 meter scale (laterally) over 1-5 km baselines. Must determine trafficability, compressibility, rolling resistance, bulk density variations, and grain sizes. Requires knowledge of regolith, in particular PSRs, of physical and geotechnical properties on surface and as a function of depth: density, granularity-size/shape distribution, age/agglutinates, shear forces, electrostatic, cohesion, thermal conductivity/capacity, electromagnetic, porosity	Science/Flight	S1.1, S1.6, S1,8
M							Requires ground truth at the 10 meter scale (laterally) over 1-5 km baselines. Must determine trafficability, compressibility, rolling resistance, bulk density variations, and grain sizes. Requires knowledge of regolith, in particular in PSRs, of mineral/chemical characteristics as a function of depth and lateral distribution	Science/Flight	S1.1, S1.3, S1.6, S1.8
H					4	Physiography and accessibility of cold traps	Need to understand slopes, elevations, block fields, cohesiveness of soils, trafficability Knowledge of environment and terrain in and around PSRs: - Thermal: Ambient and surface temperatures, radiative heat transfer properties - Terrain: slopes, rock distribution, regolith porosity and bearing strength	Science/Flight - Ground w/ Existing & New Data	S1.5, S1.6, S1.8
H					5	Charging and plasma environment within and near PSR	Understand the charge reservoirs (plasma or ground) in the low conductivity environment. The electrical 'ground' or reference point is not identified. Examine ion entry, in particular into PSRs, as sputtering loss process Plasma/charging: type and amount of charge buildup, grounding and dissipation	Science/Flight	S1.5
H					6	Composition, Form, and Distribution of Polar Volatiles	Must determine the form, concentration (including mineralogical, elemental, molecular, isotopic make-up of volatiles), and distribution of these species and how they vary from depths 0-3 m over distances of 10-100 m scales. To provide ground truth to orbital sensor datasets and characterize the regolith concentrations laterally at the 10s of meter scale over baselines of 1-5 km. Knowledge of water/volatile resources, in particular in PSRs, form, concentration, depth, distribution Requires knowledge of regolith, in particular in PSRs: physical and geotechnical - Mineral characteristics: Mineral types, element & chemical composition - Form of water (hydrated, ice, OH) and other volatiles; release as a function of temperature - Concentration of water and volatiles as function of depth - Lateral distribution of water and volatiles	Science/Flight	S1.3, S1.4, S1.5, S1.8, S2,2
M	L				7	Temporal Variability and Movement Dynamics of Surface---Correlated OH and H2O deposits towards PSR retention.	Survey surface---correlated OH/H2O at >65 degrees latitude through orbital mapping; correlate with exospheric measurements, and use results to determine the temporal and spatial distribution of water and other volatile species in lunar surface-bound exosphere.	Science/Flight - Ground w/ Existing & New Data	S1.3, S1.5, S1.8
						E. Pyroclastic Deposit Resources			
	M	M	M		1	Composition/volume/distribution/form of pyroclastic/dark mantle deposits and characteristics of associated volatiles.	Knowledge of pyroclastic deposits: location, form, distribution laterally and with depth. Requires measurements at the 10 meter scale (laterally) over 1-5 km baselines.	Science/Flight	S1.1, S1.2, S1.5, S1.8
						F. Lunar ISRU Production Efficiency 1 (Earth Testing)			
H	M	H	M		1	Component, subsystem, and system performance and operation testing on Earth (Analog and Environmental Facilities)	Excavation/resource delivery with production rate: system mass, power, rate of performance degradation. Understand drivers that effect excavation performance and efficiency.	Technology/Ground-Flt Validation	S1.10a & b
H							Regolith processing for H2O with production rate and processing temperature: system mass, power, rate of performance degradation. Understand drivers that effect extraction performance and efficiency.	Technology/Flt Demo	S1.9b
		H					Regolith processing for oxygen extraction with production rate and processing temperature: system mass, power, rate of performance degradation. Understand drivers that effect extraction performance and efficiency.	Technology/Ground-Flt Validation	S1.9a
			M				Regolith processing for production of manufacturing and construction materials: system mass, power, rate of performance degradation. Understand drivers that effect manufacturing and construction performance technique and efficiency.	Technology/Ground-Flt Validation	S1.9c
						G. Lunar ISRU Production Efficiency 2 (Lunar Testing)			
H	M	H	M		1	Component, subsystem, and system performance and operation testing on the Moon	Excavation/resource delivery with production rate: system mass, power, rate of performance degradation. Understand drivers that effect excavation techniques and transportation efficiency.	Technology/Ground-Flt Validation	S1.10a & b
H							Regolith processing for H2O with production rate and processing temperature: system mass, power, rate of performance degradation. Understand drivers that effect performance efficiency and product purity.	Technology/Flt Demo	S1.9b
		H					Regolith processing for oxygen extraction with production rate and processing temperature: system mass, power, rate of performance degradation. Understand drivers that effect performance efficiency and product purity.	Technology/Ground-Flt Validation	S1.9a
			M				Regolith processing for production of manufacturing and construction materials: system mass, power, rate of performance degradation. Understand drivers that effect performance efficiency and product quality.	Technology/Ground-Flt Validation	S1.9c

Table 3 (cont.) ISRU Strategic Knowledge Gaps

Polar Water (& polar volatiles)	Solar Wind Volatiles	O_2 from Regolith	Construction & Manufacturing	ISRU Ops	LEAG Designation	Strategic Knowledge Gap Title	Strategic Knowledge Gap Subelements	Categorization & Min. Gap Closure Approach	Architecture Integration
						III. Understanding to Work and Live on the Lunar Surface			
						A. Resource Production (subscale & human scale) - Tied to SKG I.F and I.G			
	M	H	H		1	Technologies for Excavation of Lunar Resources	Demonstrate technologies for resource excavation/extraction in non-PSR locations and resource types (mare, highland, pyroclastic glasses): excavation and transfer, dust mitigation, wear/life, energy expenditure, material selection and actuation at extremely cold temperatures	Technology/Ground-Flt Validation	S1.10a, S2.3b
H			M				Demonstrate technologies for resource excavation/extraction in PSRs: excavation and transfer, dust mitigation, wear/life, energy expenditure, material selection and actuation at extremely cold temperatures	Technology/Flt Demo	S1.10a, S2.3a
H	M	H	M		2	Technologies for Transporting Lunar Resources (Load, transport, process, dispose.)	Demonstrate regolith/resource transfer via mobility internal and external to PSRs and ingress/egress of PSRs: Energy expenditure, thermal management, power management, power storage/replenishment	Technology/Flt Demo	S1.10b, S2.3a, S2.3b
M	L	M	M		3	Technologies for Comminution of Lunar Resources	Demonstrate comminution (crushing, grinding, regolith/fracture size separation): Energy expenditure, degree of separation possible, life/wear	Technology/Flt Demo	S1.10a, S2.3a, S2.3b
	L	M	M		4	Technologies for Mineral Beneficiation of Lunar Resources	Demonstrate mineral beneficiation: Energy expenditure, degree of separation possible, life/wear	Technology/Flt Demo	S1.10a
H	M				New 5	Technologies for Regolith Processing	Demonstrate extraction of water/volatiles (Enclosed reactors, downhole enclosed, downhole open) - Enclosed reactor heating/release and capture: sealing, wear/life, energy expenditure, volatile capture and separation, thermal management - Downhole extraction heating/release and capture: surface sealing, extraction efficiency per heated volume, energy expenditure, volatile capture and separation	Technology/Flt Demo	S1.9b, S2.3a
		H					Demonstrate oxygen extraction from regolith reactors/processors: sealing, wear/life, energy expenditure, solid/gas separation and filtration, reactant regeneration, thermal management	Technology/Flt Demo	S1.9a, S2.3b
		M	M				Demonstrate metal/silicon extraction from regolith reactors/processors: sealing, wear/life, energy expenditure, product separation, reactant regeneration, thermal management	Technology/Flt Demo	S1.9c, S2.7
			H				Demonstrate production of construction feedstock	Technology/Ground-Flt Validation	S2.7
H	M	H	L				Demonstrate gas seperation and/or purification of resources/products and contaminants released during/after regolith heating/processing with and without reactants.	Technology/Ground-Flt Validation	S1.9a & b, S2.5a & b
				H	New 6	Technologies for Autonomous Operation	Demonstrate technologies and operations, and operation facilities that enable ISRU hardware to operate with no crew present and minimal or no support from human control. This includes communication needs, situational awareness, failure recovery, and remote maintanance capabilities	Technology/Ground-Flt Validation	
						B. Geodetic Grid and Navigation - Tied to SKG III.C Surface Trafficability			
				H	1	Lunar Geodetic Control	Combine topographic products from missions to produce a definitive lunar geodetic grid. - Establish geodetic reference points. - Establish and support reference (standard) time: critical for communications and synchronous operation of multiple vehicles/instruments (e.g. required for exploration/surveying)	Science/Ground	
				H	2	Lunar Topological Data	- Enable collection of a definitive global DTM with 1-2 m/pixel resolution - Understand lunar topography and precise coordinate system: map resource locations/boundaries, excavation and traverse planning, landing site selection in PSR - Plan outpost layout, surface mining operations and construction locations	Science/Ground	S1.1, 1.3, 1.5, 1.6, & 1.8
							Understand interior topgraphy of PSRs to meter resolution	Science/Flight - Ground w/ Existing & New Data	S1.3, & 1.8
				H	3	Autonomous Surface Navigation	- Ability to remotely traverse over long distances enables a) pre- positioning of assets, and b) robust robotic precursor missions. - Demonstrate autonomous surface navigation: minimize communications/Earth control for resource mapping, transfer to/from resource location to processing location - Demonstrate the capability to operate autonomously or teleoperated team of multiple robotic platforms (tasks distribution and assignment, collaborative tasks axecution, etc.) - Assess communication needs in view of minimizing Earth control/dependency, incl. specifications requirements	Technology/Ground-Flt Validation	S1.3, 1.6, 1.10a & b, S2.2, S2.3a & b
				H	4	Demonstrate Autonomous Landing and Hazard Avoidance	Autonomous landing capability for robotic missions in sunlit areas: - Landing for infrastructure emplacement - Landing for refueling and reusing landers - Landing near already existing infrastructure and hardware	Technology/Flt Demo	
							Demonstrate autonomous landing and hazard avoidance and directly land in PSR,	Technology/Flt Demo	
						C. Surface Trafficability - Tied to SKG III.A			
				M	1	Demonstrate lunar surface trafficability modeling	Geo-technical testing (especially trafficability) of prototype or test hardware in high fidelity regolith simulants	Technology/Ground	
				H	2	Demonstrate lunar surface trafficability - including in situ measurements	Characterization of geotechnical properties and hardware performance during regolith interactions, and conducting trafficability experiments in polar, pyroclastic, and young impact melt terrains	Technology/Flt Demo	S1.1, S1.10b
				H			Demonstrate trafficability (defined as the capability of the terrain to provide mobility of a particular vehicle) inside/outside the PSRs and ingress/egress of PSRs and craters: potentially low density or low bearing strength surface material, poor lighting conditions, large slopes, etc.	Technology/Flt Demo	S1.1,S1.3, S1.10b
						D. Dust and Blast Ejecta			
				H	1	Lunar Dust Remediation	Test conceptual mitigation strategies for hardware interactions with lunar fines to reduce dust prevalence. Note: dust mitigation strategies for hardware are important for ISRU hardware life/performance. Dust mitigation strategies to mitigate dust due to landers and surface movement may be tied to In Situ Construction	Technology/Flt Demo	S1.7
				H	4	Descent/Ascent Engine Blast Ejecta - in situ measurements - Tied to III.D-1	Ejected regolith velocity, departure angles, and energy in engine plume exhaust need to be measured in situ to better understand mitigation strategies, such as landing pads/berms, and separation	Technology/Flt Demo	
						E. Near-Surface Plasma Charging and Differential Electrical Charging - Tied to I.D-5			
	M	M	M			Determining near-surface plasma environment and nature of differential electrical charging at multiple lunar localities (includes PSRs)	Significant questions remain as to the degree of charging of hardware on the lunar surface, particularly night-side of the lunar terminator. Also, surface and surface-placed objects may undergo large changes in potentials during passages of solar storms. Direct observation is required in order to understand the variations of the electrical 'ground' defined by the plasma currents to an object placed on the surface.	Science/Flight Demo	
H							In PSRs, the lack of an obvious charge reservoir (i.e., low conductivity surface and obstructed plasma) suggests the possibility of poor electrical dissipation for tribocharging objects like drills, and rover tires.	Science/Flight Demo	
						F. Energy Production and Storage - Polar Missions			
				M	1	Energy Storage - Non Polar Missions	Non-polar regions experience 14 Earth-days without sunlight; needs for entire lunar night in the 100s to 1000s kW-hrs - Demonstrate energy storage and transfer in equatorial lunar day/night (28 day) cycle - Survive lunar night	Technology/Ground	
				H	2	Energy Storage - Polar Missions	Polar missions may be positioned in areas with extended solar availability; blackouts may extend to 3-5 days requiring 100s of kW-hours - Demonstrate energy production, storage, and transfer for hardware with PSRs: stationary units; mobile units, internal power (nuclear) vs external power (solar, laser, microwave beaming) - Demonstrate energy production, storage, and transfer in near-permanently lit locations	Technology/Ground	
				M	3	Power Generation - Non Polar Missions	Non-polar missions will require 10s to 100s of kW via deployable solar arrays or nuclear power systems on the lunar surface. Of particular concern is providing power through the lunar night. - Demonstrate energy production and transfer in equatorial lunar day/night (28 day) cycle - Survive lunar night	Technology/Ground	
				H	4	Power Generation - Polar Missions	Low grazing angles of sun light at the lunar poles requires solar arrays with rotational tracking, preferably on a high mast, or nuclear power systems on the lunar surface - Demonstrate energy production, storage, and transfer for hardware with PSRs: stationary units; mobile units, internal power (nuclear) vs external power (solar, laser, microwave beaming) - Demonstrate energy production, storage, and transfer in near-permanently lit locations	Technology/Ground	
				M	5	Lander Propellant Scavenging	Determine the efficiency of extracting residual oxygen and fuel (ex. hydrogen) from tanks in lunar landers.	Technology/Ground	
						G. Radiation shielding			
H			H			Test Radiation Shielding Technologies	Protecting human crews beyond the magnetic fields of the Earth from space radiation is critical. Testing radiation shielding technologies and operational approaches, are required - Knowledge of the predicted average radiation dose from GCRs and SPEs at the expected landing polar location, before any shielding is applied. - Measure radiation through bulk regolith, constructed materials, water, and in situ produced plastics	Technology/Ground-Flt Validation	S1.8
						H. Micrometeroite shielding			
			H			Test micrometeroite protection technologies	- Knowledge of the predicted average micrometeroite dose at the expected landing polar location, before any shielding is applied. - Measure micrometeroite shielding performance of bulk regolith and constructed materials.	Technology/Ground	S1.5 & S1.8

TAXONOMY

ISRU Functional Breakdowns

The development and incorporation of ISRU systems and capabilities into robotic and human mission architectures that can harness and utilize resources found at the site of exploration, instead of transporting mission consumables from Earth, covers a wide range of potential applications, technologies, and technical disciplines. As shown in Figure 1, ISRU covers three broad areas: In-Situ Propellant & Consumable Production, In-Situ Construction, and In-Space Manufacturing with ISRU-Derived Feedstock. To properly understand, track, and coordinate development activities, each of these three broad areas needs to be further subdivided into functions and sub-functions that define the needs, requirements, and interfaces that will eventually enable end-to-end ISRU capabilities. The following sections and tables provide the functional breakdown for the main three areas of ISRU that will be utilized in subsequent sections of the report.

In-Situ Propellant and Consumable Production

In-Situ Propellant and Consumable Production (ISPCP) involves systems and capabilities that can harness and utilize resources found at the site of exploration for the production of propellants and mission consumables, instead of bringing everything from Earth. To enable the complete resource-to-product chain, ISPCP capabilities must cover a wide range of potential processes, technologies, and technical disciplines. As depicted in Figure 3., there are four main sub-functional areas for ISPCP:

- Destination Reconnaissance and Resource Assessment
- Resource Acquisition, Isolation, and Preparation
- Resource Processing for Production of Mission Consumables
- Resource Processing for Production of Manufacturing and Construction Feedstock Materials

Destination Reconnaissance and Resource Assessment involves the characterization and mapping of physical, mineral, chemical, and water/volatile resources, terrain, geology, and the environment. Resource assessment is performed from orbit and on the surface, and surface missions will most likely progress from initial short-duration missions with limited instrument/assessment capabilities to longer-duration missions with suites of instruments to thoroughly assess the resources available for site selection and mine operation planning. Destination Reconnaissance and Resource Assessment overlap with and has significant commonalities with other mission activities such as science in general, mission site selection, and landing site and outpost planning.

Resource Acquisition, Isolation, and Preparation involves functions associated with acquiring, separating, and preparing resources from their natural state or location. This functional area includes activities such as i) excavation and drilling for acquisition; ii) adsorption, membranes, cryogenic distillation, and mineral beneficiation for isolation; and iii) crushing, grinding, and size sorting for preparation. For trash and waste, this also include disassembly, shredding, and sorting. Besides acquiring, separating, and preparing resources, this functional area also involves delivering and transferring extracted and prepared resources to subsequent resource processing units.

Resource Processing for Production of Mission Consumables involves the extraction and processing of resources from prepared and delivered resources into products that can be used for critical mission consumables such as rocket propellants, fuel cell reactants, and life support commodities such as water, oxygen, and nitrogen. For lunar exploration, the two most important resource processing activities are oxygen extraction from lunar regolith minerals and water extraction from permanently shadowed regions. The water extracted can be used as-is or further processed into oxygen and hydrogen. On Mars, resource processing also includes water extraction and processing from in-situ sources as well as Mars atmosphere carbon dioxide processing into oxygen and hydrocarbon fuels such as methane. Regolith processing for oxygen extraction can include thermal, electrolytic, chemical, and/or biological reduction of regolith with subsequent reactant/product separation, cleaning, and storage. Mining Polar Water and Volatiles involves excavation and/or in-situ processing of water/volatile-laden regolith in permanently shadowed regions (PSRs) of the lunar poles via thermal and/or radio-frequency (including microwave) energy to release water and volatiles present with subsequent separation, cleaning, processing, and storage. Since Mars has three different water sources of interest, granular soils and hydrated minerals at the surface and sheets of ice under the surface, each Mars water source involves different water extraction/mining techniques.

Resource Processing for Production of Manufacturing and Construction Feedstocks involves synergistic functions and technologies utilized in the production of mission consumables to produce feedstock that can be subsequently utilized for manufacturing and construction capabilities. Some processes utilized for extracting oxygen from regolith also may concentrate or separate metals in the regolith as well. While similar, the functions are still separate since they will be tailored to use specific resources, create specific end products, and operate at different processing rates. Close development of the parallel functions is warranted to minimize development cost and risk. Since one of the resources of interest for production of manufacturing and construction feedstocks includes crew trash and waste, close development and coordination of resource preparation and processing with the Advanced Life Support and Human. At this time, primary feedstocks of interest include bulk and prepared/beneficiated regolith, metals and ceramics from regolith, and plastics derived from in-situ processed resources. Recycling of plastics and previously used parts is covered under In-Situ Construction and In-Space Manufacturing.

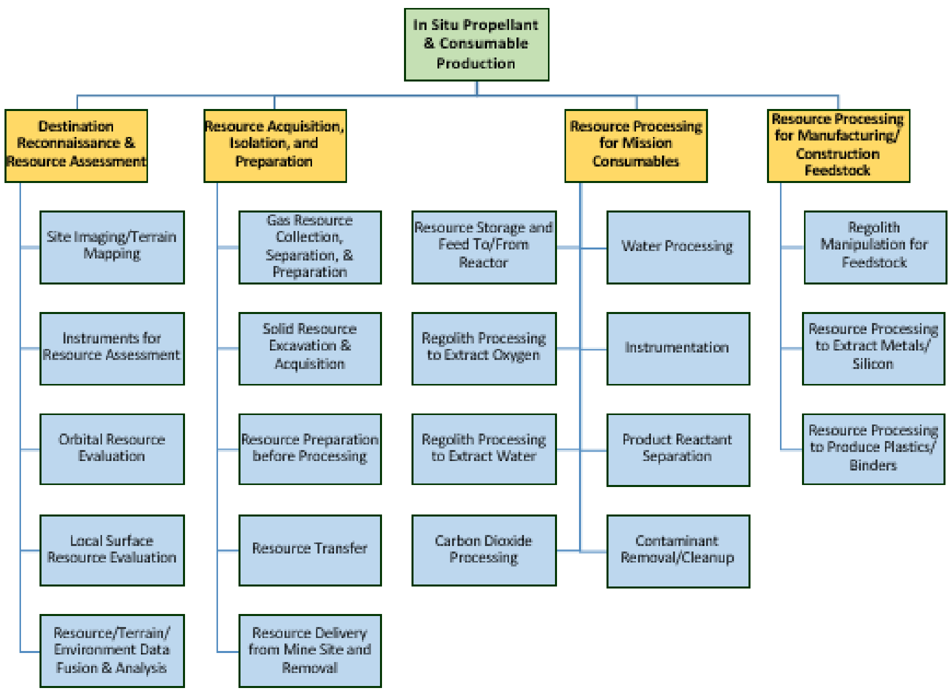


Figure 3. In-Situ Propellant and Consumable Production Functional Breakdown

In-Situ Construction

In-Situ Construction involves activities such as site assessment and planning, area clearing and levelling, surface compaction and stabilization, berm building, and construction via sintering, moulds, bricks/slabs, and/or additive manufacturing. For the realization of sustainable exploration missions and ISRU infrastructure development, it is an important activity and covers the aforementioned range of activities. Figure 4 provides a breakdown of the In-Situ Construction topic and associated activities that fall into this taxonomy. It provides for each main steps the key activities involved from site planning & design to Inspection, Maintenance & Life Cycle (including the aspects of Construction Waste and Recycling) and the construction activity itself.

Site planning and preparation covers a range of preparatory activities, with significant influence from terrestrial experience and construction heritage. The establishment of construction best practices and standards will be required, with consideration given to the unique environment presented on a planetary surface such as the Moon or Mars. Master planning and facility management, and their potential impact on operations, need to be considered at this stage. Terrain modification, via excavation, rock clearing, or packing, is listed here as precursors to construction and assembly activities, though they may arise incidentally from other ISRU processes such as regolith harvesting for oxygen production.

Construction material preparation covers a range of activities classically associated with conveyance, beneficiation, and comminution. As an example, the collection of surface regolith, mineralogical/particle size sorting, and quality control of this feedstock prior to a construction stage would be considered a preparatory activity. Quality assurance, process, product inspection and management, also important for other ISRU derived capabilities such as in-space manufacturing, also needs to be applied for construction stages.

With regards to construction, feedstock used in construction activities may utilize Earth-provided binders, but should primarily utilize in-situ material such as bulk or processed regolith. Potential products/applications may include radiation shields, landing/launch pads, roads, protecting walls, and habitats, covering both horizontal and vertical construction modalities. These activities may be extremely important for infrastructure and crew protection at locations that are repeatedly visited. For long-term surface operations, more complex construction tasks such as building habitats/structures may be required. Techniques such as additive construction have received much attention as an approach to realize such construction projects, however more mundane techniques such as casting, brick production, and pressing should be highly considered. Post-construction finishing is also a topic here, where the final ISRU construction might require a final treatment stage. This would cover the fitting of elements that cannot be reasonably constructed in-situ, for example attaching hatches or piping to an ISRU produced radiation shield, or thermal post-processing of an ISRU derived landing pad.

Lastly, inspection and maintenance of ISRU derived construction elements needs to be considered. Again, significant terrestrial heritage in this domain exists and would need to be adapted to the unique nature of ISRU construction on a planetary surface. Questions relating to the inspection of compliance of ISRU constructed elements need to be defined – for example, what are the acceptable functional characteristics for an ISRU landing pad in order to credibly meet its design intent? Can we use technology (e.g. embedded or IoT sensors) to enable in-line monitoring of ISRU produced elements? As with any construction project, maintenance and upkeep are topics that must be considered – preventative maintenance action and ease of repair (e.g. vs environmental damage and general wear & tear) are challenges that will need to be considered for in-situ construction.

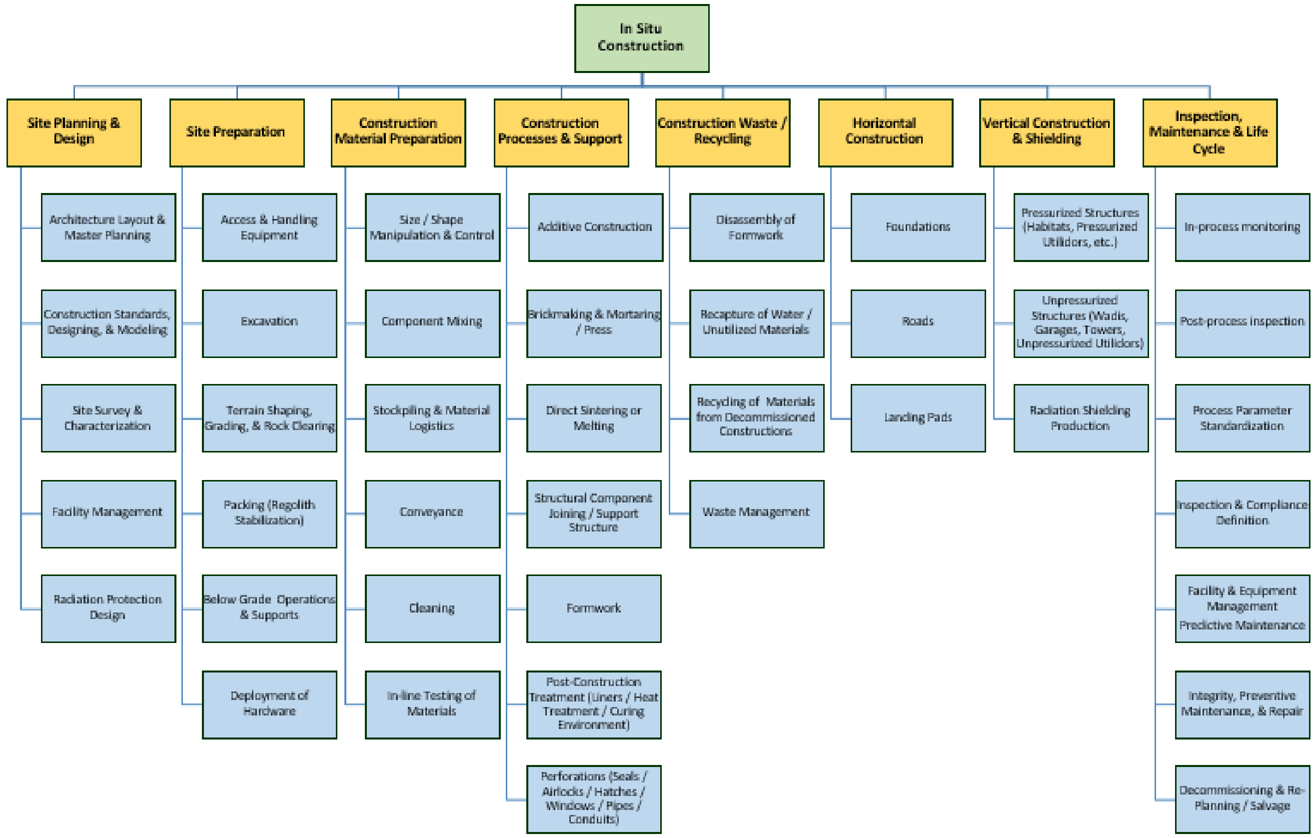


Figure 4. *In-Situ* Construction Functional Breakdown

In-Space Manufacturing with ISRU-Derived Feedstock

In-Space Manufacturing (ISM) with ISRU-Derived Feedstock involves the creation of feedstock from local resources and the modification of equipment, to utilize these feedstocks for the production of individual parts, the assembly of more complex hardware or the repair and maintenance of assets. ISM involves manufacturing techniques (additive, subtractive, and near-net-shape forming), non-destructive evaluation, joining, repair, and assembly. The ability to manufacture and repair hardware is critical for long-duration human missions to minimize logistics and spares inventory/mass, and minimize mission risk from delayed replacement delivery due to the distance from Earth or transportation failures. ISM with ISRU-Derived Feedstock effort differs from advanced space manufacturing technology development by specifically focusing on the use of in-situ derived materials and feedstock for manufacturing, as opposed to feedstock supplied from Earth. It should be noted that development and operation of ISM hardware and software with terrestrial feedstock materials falls outside the scope of ISRU. However, this overall capability is included in this section and the report since ISRU developers and final products will have to interface and coordinate with ISM for manufacturing feedstock type, quality, and quantity. In addition, in-situ manufacturing may involve, in some cases, the combination, or ISRU-derived feedstock and materials brought from Earth.

While quite different in many circumstances, ISM can share technology approaches and operation similarities with In-Situ Construction. Moreover, as depicted in the Functional Flow Diagrams, to fully understand the influence and impact of ISRU, it is important to include In-Situ Propellant & Consumable Production, In-Situ Construction and In-Space Manufacturing as an integrated ecosystem. In-Space Manufacturing as demonstrated in Figure 5 includes the manufacturing of components all the way to maintenance, inspection & life cycle, including in-situ assembly processes. Metallic and ceramic material feedstock can be derived from the regolith, while polymer materials could be produced using in-situ resources such as volatiles. Feedstock can also be obtained by recycling previously used materials. The regolith itself can also be used as a feedstock following minor pre-processing, e.g. sorting of grain sizes or magnetic separation.

Depending on their nature, the various manufacturing processes may require prior feedstock preparation, such as powder atomization or filament extrusion for additive manufacturing. Subtractive manufacturing processes start from a preliminarily prepared workpiece. Individual parts can be manufactured by additive, subtractive, or net-shape forming processes. Composite material parts can also be produced, e.g. by placing regolith-based reinforcements in a matrix. The individual parts could be joined into more complex assemblies. The development of reliable in-situ manufacturing processes requires the establishment of in-process monitoring capability, as well as appropriate methods for product inspection and equipment maintenance. To fully achieve the sustainability allowed by in-space manufacturing, the ability to recycle material into new feedstock and the understanding of the impact of such recycling operations on the product quality needs to be ascertained.

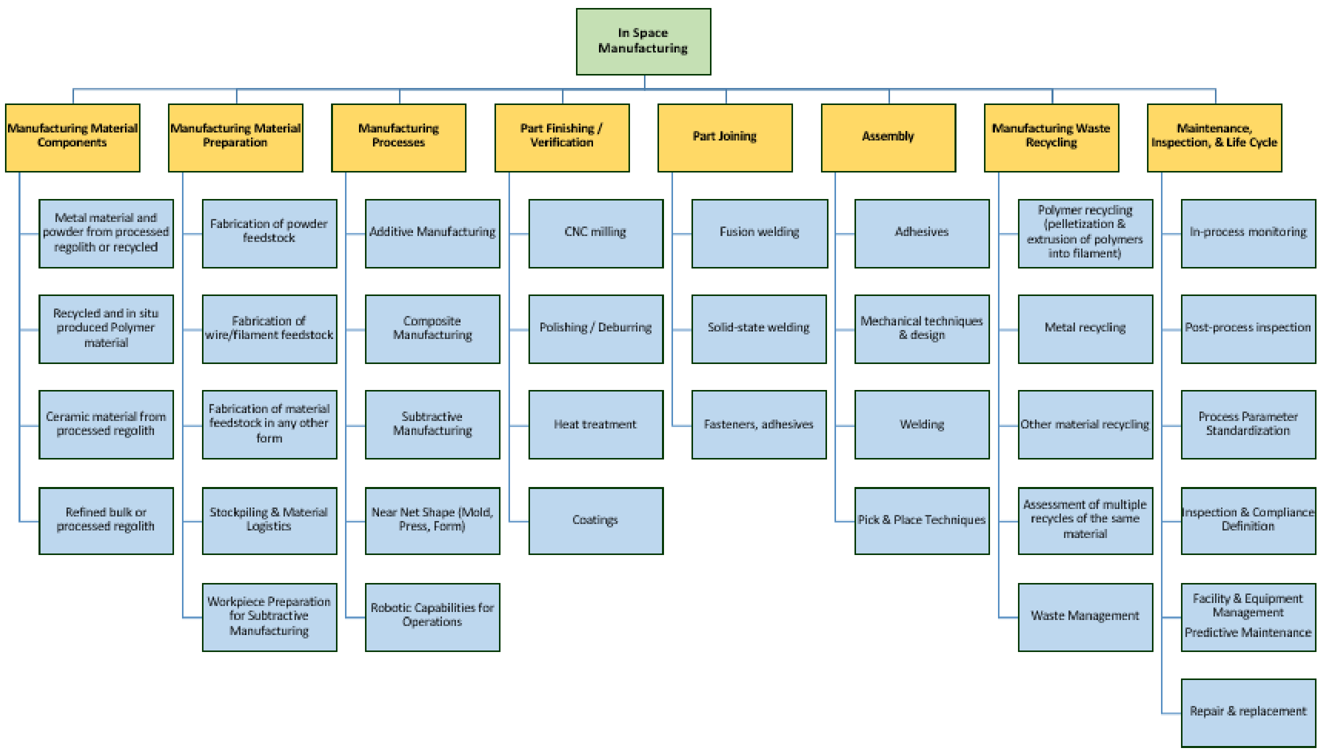


Figure 5. In-Space Manufacturing Functional Breakdown

ISRU Functional Flow Diagram

The previous *ISRU Functional Breakdown* section provided descriptions and tables to help categorize and track critical functions and sub-functions that need to be developed to achieve ISRU capability and system objectives. However, the functional breakdown tables do not convey how each function and sub-function needs to interact and connect with each other to achieve the final end-to-end capability needed to generate ISRU products of interest. To help understand how each function or sub-function interacts and influences other areas of ISRU, integrated functional flow diagrams have been created (see Figure 6). These functional flow diagrams provide a visual representation of the flow of work and resources from one-step to the next until the final products are achieved. The overall function flow involves seven major interconnected functions as described below. Please note that the dashed boxes in Figure 6 denote the seven major functions, and encompass the sub-functions that are involved in the major function. Also, note that Life Support and Habitation Systems is depicted in Figure 6. While this major function falls outside the scope of ISRU and the ISRU Gap assessment, the team believed that it was important to show the interconnection of 'resources' and products between ISRU and Life Support systems.

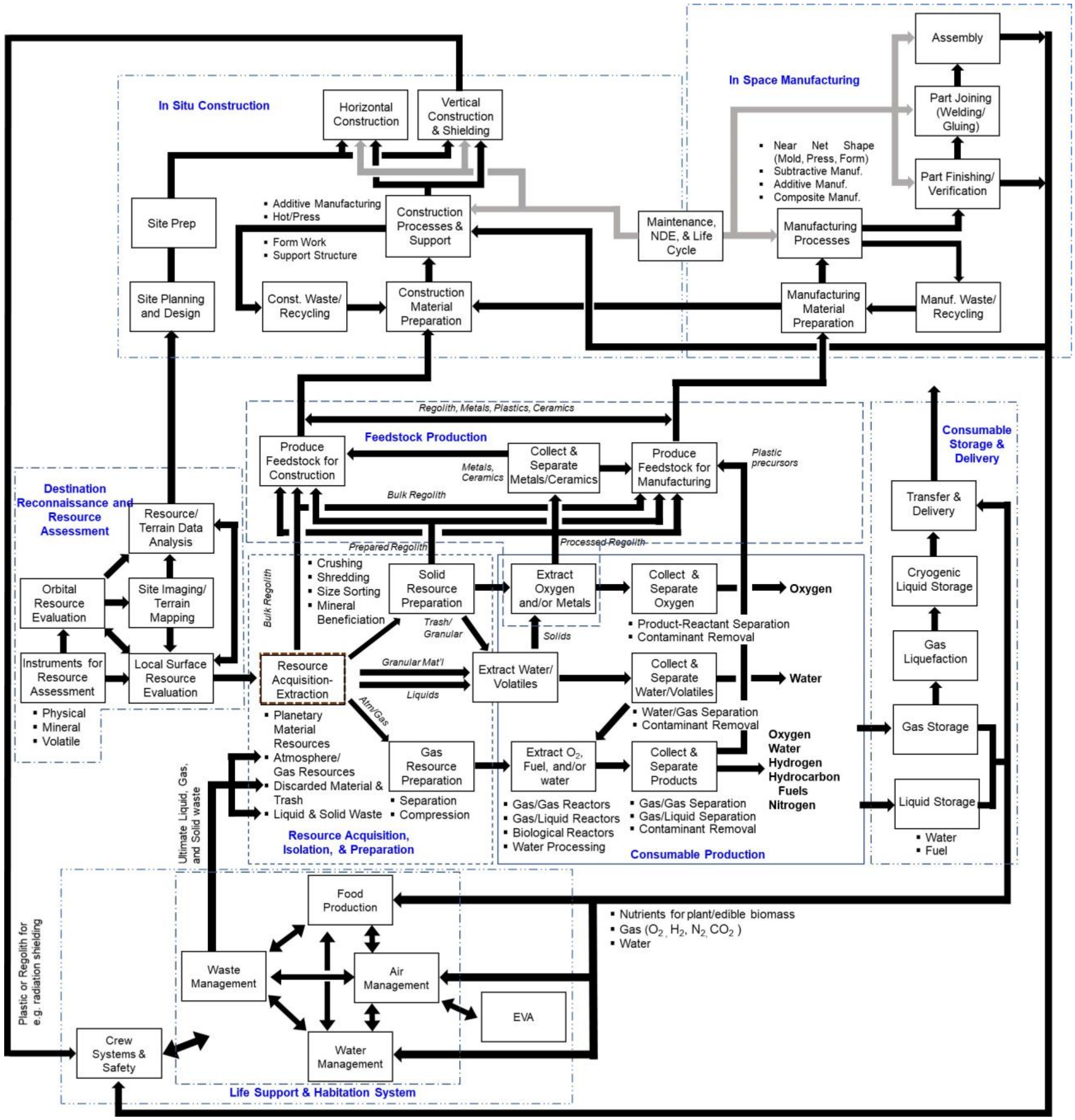


Figure 6. Integrated ISRU Functional Flow Diagram (Including ties to Life Support)

Destination and Reconnaissance and Resources Management

Generally speaking, ISRU systems are dependent on what resources exist resources (form and concentration) and where they are found. Therefore, this function focuses on establishing this information with an emphasis on measurement and ground truth. This effort starts from a global perspective with imaging and multi-spectral remote sensing to determine the abundances of relevant and desired resources and the terrain and conditions in which the resource is found. Further and more complex operations involve in-situ verification (or 'ground truth') by taking surface and subsurface measurements and samples and confirming the models developed from remote measurement datasets. High-resolution cameras and various spectrometers will generate data from orbit. Stereo terrain imaging, mass spectrometry, Raman lasers, Mossbauer effect and alpha particle detectors can be used amongst others on the ground. Sufficient coverage in-situ is needed to ensure remote sensing models are accurately correlated for use in future landing site selection. One very specific in-situ measurement, is volatile content (ice, hydrogen, water, methane). This measurement requires specific instruments and usually involving ovens or sample heating units.

The data obtained from orbital and surface measurements are used to build a picture of mineralogy and the ambient environment that can be used by mission planners and engineers to develop technology with confidence that the resource exists and can be extracted, and commercial investors to develop a realistic business case. There are factors such as granularity, form and how minerals are bound together that are important to understand and can impact the chemistry and process needs to access that target resource in an environment such as the lunar, Martian, or asteroid surfaces.

Resource Acquisition Isolation and Preparation

When one knows which resource is of interest, possibly more than one, accessing it becomes a driving aspect of the ISRU system design. The simplest approach is to reach and excavate material and/or acquire gases directly from hardware attached to the landing system. The process starts with selecting a method of excavating solids/pumping gases. There are typically multiple options with the final choice being a balance of throughput, complexity/reliability, and energy (like most aspects of ISRU). Scooping, drilling clamshell end effectors can be placed on a robotic arm or some kind of platform. Dexterity and the force applied to the surface are important. Pressures to be obtained to draw in ambient gases in an atmosphere is another example. A specific method of extracting the solids depends on the depth and the degree of density (how compact the material is). Expanding the point of where you collect the solid. The end effector can also be placed on a moving system to access areas either where landers cannot go (maybe a shadowed crater when trying to access ice) or more surface area for larger systems that need significant amounts of solid raw material. The system must also deal with gaseous and volatile resources as these are relevant and can be used, identified, and common by prospecting previously, in a given location.

Depending on the factors of location, ambient pressure, solid bulk density, target mineral, and state of matter, various interfaces are created. They can be categorized in three ways. 1. Providing a sealed system that can capture and pipe gases to a preparation stage. 2. Depositing solid material in a receptacle ready for sorting shredding, beneficiation (discarding un-wanted constituents by mineral) or direct use. 3. Waste outlets. The first two are outputs to be processed into usable forms. The third is an input considered further in the next paragraph.

The waste is a point not mentioned thus far, particularly its removal/transport and has inputs and outputs to the consumables production and input to resource acquisition. This depends primarily on the throughput. If there is a small-scale time-restricted ISRU system, it is perhaps not a driver of design. However, if at a large production scale, management of waste such as slag or unwanted grain sizes (fines or pebbles) becomes required. Mobile solid waste removal (as it cannot simply be allowed to pile up) applies. A mobile system of rovers and articulation technology will be needed. This aspect will interface with production and/or storage waste. Input waste is also a factor, as it provides a source of some consumables that can be recovered.

Consumable Production

Once the resource has been acquired, the next step is to process the resource into products. As was mentioned previously in the report, the production of mission consumables can have a significant impact on the overall architecture, especially launch mass. There are different types of consumables to consider. The first are those that are products for other users. These can be oxygen, gases from atmospheres, extracted water, metals for construction, and/or other useful volatiles. Another type is those that are needed to support processing to obtain a new product. Oxygen and hydrogen for example can be considered intermediate products, which can be consumed to produce other products of value. Both consumable production aspects are important as we aim for a system which is as closed as possible and utilizes resources to the maximum extent possible to create a wide range of mission support products that no longer need to be brought from Earth.

To obtain a product:

- Oxygen can be separated from the solid metal oxides within. The inputs can come from three sources provided by resource acquisition function providing in a manageable form. Metal oxides, solid volatiles (e.g., ice and rock), and trapped gases. Reduction process technology is required to extract oxygen. Some examples are electrochemical, use of hydrogen and methane, and higher temperature oxide melts. Each has different temperature requirements and chemistry. This is then collected and sent for storage or use.
- Gas separation. Atmospheric gases can be acquired and the useful parts separated by physical (membranes), chemical (adsorption), thermal (condensation/freezing), and/or biological (aerobic and anaerobic) processes can be used for gas separation.
- Collection and separation of volatiles. Some areas of excavation may already contain useful readily made products, such as water or other volatiles that can be found in lunar and Mars regolith. In this case, it is a question of containment and rejection of unwanted solids. For example, separating ice from rock in the Moons permanently shadowed regions.

To obtain consumables in multi-step processes:

- Some processes require multiple steps to reach the final product desired from the initial resource. In almost all cases, each step includes products, unreacted, reagents, and contaminants, impurities, or undesired side products. This requires additional collection, separation, purification, and recycling steps to minimize waste and increase final product generation. For example, conversion of carbon dioxide into oxygen and methane requires unreacted hydrogen to be separated from methane, and water to be separated and processed so hydrogen can be recycled.

Feedstock Production for In-Space Manufacturing and In-Situ Construction

Consumable Production is aimed at high-value mission consumables such as water, oxygen, and fuels. In the process of making these consumables from lunar regolith/Mars soils, constituents that can be utilized for In-Situ Construction and In-Space Manufacturing are also partially or fully produced as well. Metals extracted from minerals, bulk and refined regolith, and plastics and other binders are examples of feedstock material constituents of interest. Feedstock for in-situ construction and in-space manufacturing operations will most likely involve the preparation and blending of multiple constituents. Some of the items produced from Consumable Production, such as metals may require further processing to increase the concentration or alloy the metals of interest. This step in the ISRU Functional Flow diagram provides the basic constituents that will be used in subsequent processing as depicted in Figure 6 for In-Situ Construction and ISM with ISRU-derived Feedstock.

Consumable Storage and Delivery

Once a product has been generated, it needs to be stored and eventually delivered to the user/customer. Since most mission consumables are either gases or liquids, the functional flow diagram focuses strongly on these product forms. To minimize storage mass and weight, oxygen, methane, and hydrogen will most likely need to be liquefied. This is particularly true for large amounts of these products for propulsion applications. Fuel cells and crew life support consumables may be stored and delivered in high-pressure gaseous form.

In-Situ Construction

In-Situ Construction involves all the steps needed to locate, prepare, and construct horizontal and vertical structures on the Moon and Mars. There are three independent but linked efforts involved in In-Situ Construction: the site planning/preparation flow, the material preparation and construction processing flow, and the evaluation, maintenance, and life cycle flow. In-Situ Construction also has direct ties to four other major functions: Destination Reconnaissance and Resource Assessment (DRRA), Feedstock Production, In-Space Manufacturing, and Crew Safety. From DRRA, In-Situ Construction receives information that it can use to start the site planning process. From Feedstock Production and In-Space Manufacturing, In-Situ Construction receives construction feedstock constituents. From In-Space Manufacturing and Crew Safety, In-Situ Construction receives support for construction activities. Because of the close nature between In-Situ Construction and In-Space Manufacturing with respect to technologies, processes, and products, Maintenance, Non-Destructive Evaluation (NDE), and Life Cycle activities are shared between the two.

In-Space Manufacturing

It is important to show the linkage and flow from ISRU functions to In-Space Manufacturing, as products made from ISM will be highly dependent on the amount and quality of the feedstock derived from in-situ resources. The in-situ derived feedstock quantity and quality are expected to evolve over time from just using bulk or partially refined regolith to raw metals from oxygen extraction processes, to highly refined metals as experience and capabilities evolve.

Life Support and Habitation Systems

While Life Support and Habitation Systems also fall outside of the scope of the ISRU Gap Assessment, it is important to show the linkage and flow from of ‘resources’ and products between ISRU functions to Life Support and Habitation Systems. The ISRU Gap Assessment team engaged subject matter experts from several space agencies to ensure proper communication and coordination to depict these interactions properly.

ISRU IN MOON/MARS HUMAN EXPLORATION

Human Lunar Exploration: Global Exploration Roadmap and Artemis

In 2006, 14 space agencies began a series of discussions on global interests in space exploration. Known as the International Space Exploration Coordination Group (ISECG), these space agencies took the unprecedented step of elaborating a vision for peaceful robotic and human space exploration, focusing on destinations within the solar system where humans may one day live and work, and developed a common set of key space exploration themes. This shared vision was first articulated in *The Global Exploration Strategy: The Framework for Coordination*, which was released in May 2007. In September of 2011, the ISECG released the first Global Exploration Roadmap (GER) which reflects the international effort to define feasible and sustainable exploration pathways to the Moon, near-Earth asteroids, and Mars. Since then, two updated ISECG GERs have been released (2013 and 2018). In December of 2017, the US President directed NASA to lead a human return to the Moon and beyond with commercial and international partners. Two years later, the US National Space Council under the leadership of the Vice President, directed NASA to lead the effort to send the first woman and next man to the Moon within five years. To achieve those goals, NASA has implemented the Artemis program. Human lunar exploration in the Artemis program is divided into two major phases. The first phase involves robotic, pre-deployment, and human missions to achieve Landing Humans on the Moon by 2024. The second phase involves missions to Extend Lunar Missions and Preparing for Mars.

Since the release of the updated GER in 2018, many ISECG space agencies have set new national priorities and intensified and accelerated lunar exploration plans. These ambitious exploration plans, coupled with new agency participants in the ISECG, created the opportunity to produce a Supplement to the 2018 GER, issued in 2020, that extends and refines the ISECG Lunar Surface Exploration Scenario. This 2020 scenario update supplements the 2018 GER by introducing the newly joined ISECG organizations and updating agency lunar exploration plans. This GER Supplement also includes a newly formulated set of common objectives for a sustainable lunar surface exploration campaign and the updated Lunar Surface Exploration Scenario describes the architectural elements and the exploration campaign that progressively meet these lunar surface exploration objectives and serve as preparation for missions to Mars and for further activities on the Moon.

Human Lunar Exploration Objectives

At the time of performing the ISRU Gap study and writing this report, an official and internationally-accepted human lunar architecture does not exist. Therefore, the study team utilized reports and information from the NASA Constellation program, past Global Exploration Roadmaps, the current planning activities for the US Artemis program, and international space agency coordination activities associated with the ISECG as the basis for evaluating and incorporating ISRU into future human lunar exploration plans. Based on these efforts, the study identified three main driving objectives and architectures for Lunar ISRU development and insertion plans.

1. Lunar Science and Sustained Human Surface Exploration
2. Enable Commercialization of Cis-Lunar Space
3. Preparation for Human Mars Exploration

The first main objective/architecture is to significantly advance our understanding of lunar resources, enable sustained human presence on the Moon, and enable sustained and evolvable human lunar surface exploration. To accomplish this, the space agencies will perform orbital and lunar surface characterization and resource assessment missions to fulfil scientific and exploration goals leading to a better understanding of the lunar surface and site selections for human exploration and sustained operations. At the same time, space agencies will perform extensive ground development efforts leading to technology and subsystem flight demonstration and validation missions using space agency developed and commercially developed hardware, such as NASA's

Commercial Lunar Payload Services (CLPS) landers, for example. Before full implementation of ISRU products into a mission-critical role, end-to-end operations at a mission-relevant scale and duration that prove the capabilities of the products can meet mission architecture requirements will need to be performed. The products from these early missions may be used in a mission enhancing role such as extending crew surface and extra-vehicular activities (EVAs) with in-situ produced oxygen, or demonstrate robotic surface propulsive hopping or ascent with in-situ produced propellants.

The second main objective is to enable commercialization of cis-lunar space where space agencies will use lunar ISRU to enable economic expansion on Earth and into space. The ISRU capabilities defined and discussed in this report can be turned over to commercial providers once adequately demonstrated for increased space commercial activity and cis-lunar transportation. Leveraging such public-private partnerships will require ISECG member agencies to work closely with their associated technology transfer offices, in alignment with their respective IP management practices. It is expected that propellant/consumable needs for cis-lunar commercial activities will be one to three orders of magnitude greater than needed by space agencies for initial sustained lunar exploration[1]. Once adequately demonstrated for increased space commercial activity, the strengthening partnerships and commercialization process represents another enabling opportunity to innovate to realize further efficiencies and scalability. This can facilitate continuity of activities that are initially led by government, thus incentivizing the growth of commercial activities and industry participation. In addition, since many of the technologies, systems, and operations are relevant to terrestrial mining, renewable energy, and construction, commercial partnerships and opportunities for terrestrial applications and associated socio-economic benefits are increasingly accessible and will be pursued.

Lastly, the third main objective is to reduce the risk and prepare for human exploration of Mars. To accomplish this, space agencies will develop and demonstrate technologies and systems that are not only useful for lunar exploration and ISRU but are also applicable to Mars. While the environment and surface material of the Moon and Mars are different, there are many similar technologies and systems to process the resources that can be leveraged. Space agencies and commercial entities can leverage lunar missions for ISRU operational experience and mission validation for Mars. There are several lunar ISRU operations, such as regolith excavation and processing as well as pre-deployment, remote operation and autonomy, and product/propellant storage and transfer, which are needed for Mars ISRU that can be demonstrated and perfected on the Moon before going on to Mars. For Mars ISRU technologies and processes that do not have direct ties to either lunar oxygen extraction or polar water mining capabilities, separate dedicated development efforts and missions will be undertaken to support the human Mars surface exploration.

Underlying the challenges of human lunar exploration, there are also the important inspirational aspects to this mission; promoting public awareness of human space exploration, inspiring the public through demonstrating the possibilities of science, technology, and innovation, and encouraging the younger generation to join STEM fields in education.

Human Lunar Exploration Phases

At the start of the ISRU Gap Study, the last shared vision for human exploration of space from the international space agencies that make up the ISECG was the 2018 GER. The GER is based upon a common set of exploration goals, objectives, and identified benefits to humanity. Since its release, there has been a renewal of interest and focus on lunar exploration, both for its scientific opportunities and to demonstrate capabilities that will also prepare for human missions to Mars and for further activities on the Moon. In August 2020, The ISECG released *the Global Exploration Roadmap, Supplement August 2020, Lunar Surface Exploration Scenario Update*. This document provides a table of twelve key Lunar Surface Exploration objectives; one of which is to "Demonstrate in-situ resource production and utilization capability sufficient for crew transportation between lunar surface and Gateway and lunar surface utilization needs".

[1] Ref. Commercial Lunar Propellant Architecture Study

This document explains that the human Lunar Exploration Architecture can be divided into the following 3 Phases:

1. "Boots on the Moon"
2. Expanding and Building
3. Sustained Lunar Operations

Using this document and working with the ISECG International Architecture Working Group (IAWG), the ISRU Gap Study team defined goals and objectives for ISRU for each of the three lunar exploration phases, as depicted in Table 4, Table 5, and the subsections below.

Phase 1: Boots on the Moon – ISRU Objective: Prospecting, Characterization, and Technology in Lunar Environment

For ISRU, there are two overarching goals for Phase 1.

- Robotic prospecting and characterization of the environment, regolith, and operation of hardware under lunar conditions.
- Initiation of resource utilization technologies and surface operation demonstrations

Missions in this Phase are assumed to be all robotic (with unpressurised rovers) precursor missions up to the next human landing mission. The overall objective is to obtain relevant and necessary data on resources, regolith characteristics, the environment, and hardware operation under actual lunar surface conditions to inform future ISRU architecture decisions. Demonstrations of resource utilization technologies and surface operations will start in this phase, with the final objective to validate resource utilisation technologies from prospecting, product storage to transfer.

In this Phase, countries and international space agencies will explore and characterise lunar regolith in non-polar or polar (illuminated or shadowed) regions with regards to water, oxygen, and other volatile's abundance. The demonstration of ISRU concepts and functions at subscale is also envisioned.

Key aspects of Phase 1 are depicted in Table 5 and include the following:

- Focus on resource assessment (geotechnical/physical, mineral/chemical, and volatile) and ground-truthing of potential sites, both polar (sun-lit regolith and ice volatiles) and non-polar (regolith and solar wind volatiles);
- Understand the concentrations of lunar ice, minerals (e.g. oxygen content, metals), and solar wind volatiles in regolith for each potential site;
- Address questions regarding the form, composition, and depth of lunar ice, minerals and other volatiles via ground-truth measurements for subsequent phases;
- Understand the lunar regolith dust properties and demonstrate mitigation techniques for long-term surface operations including radiation/micrometeoroid shielding materials and concepts;
- Provide ground-truth data to refine orbital measurements and environment models;
- Demonstrate ISRU concepts and functions for
  - Oxygen extraction from regolith and polar water (and volatiles) extraction capabilities;
  - Water/oxygen/volatile purification techniques required for subsequent utilization;
  - Regolith processing capabilities to extract metals and other products;
  - Regolith excavation and comminution (crashing, sorting and mineral beneficiation) capabilities considering system performance, operation, lifetime/wear;
  - Regolith transportation capabilities.

- Waste management as a transversal element in the ISRU value chain.

Phase 2: Expanding and Building – ISRU Objective: End-to-End Demonstrations and Small-Scale Production

The overall objective of this phase is to demonstrate the capability of small-scale ISRU production (ISRU pilot and production plants). For ISRU, there are two overarching goals for Phase 2.

- Robotic/crewed missions to demonstrate and verify elements and integrated capabilities to prove sustainable operations
- Provision of ISRU products for non-mission critical applications to enhance mission and reduce risk for large scale production and use

Phase 2 starts right after the initial human landing missions that demonstrate initial crew surface operations and science. Phase 2 will utilise a combination of robotic (including utility rovers) and crewed missions to demonstrate and verify individual elements of the integrated ISRU capabilities necessary to support sustainable operations. During this phase in the human lunar architecture, a stronger focus will be placed on integrated systems to achieve desired ISRU capabilities and products. A gradual shift in the type of surface operations towards an increased mining perspective is expected, also leveraging on non-space industries. The lunar architecture is aimed at demonstrating ISRU at the polar region where sustained operations are likely to occur. Ultimately, end-to-end demonstrations and small-scale production should consider scalability to sustained operations.

Key aspects of this scenario are:

- Demonstrate ISRU capabilities and technologies as proving ground for lunar sustainability, with view on Mars-forward applications and commercial advancement;
- Grade and quantify ice water deposits in order to support the planning and selection of operational sites for resource extraction;
- ISRU integrated systems for validation of end-to-end demonstrators for mining, production, liquefaction, (cryo-)storage, and transfer of consumables (e.g. either water-based oxygen/hydrogen or oxygen from regolith), including
    - Oxygen as propellant for refuelling scenarios;
    - Oxygen/hydrogen for energy storage systems (fuel cells) for:
        - Regenerative system (e.g. for night survival);
        - Non-regenerative system (e.g. powering rechargeable vehicles);
    - Water/oxygen for crew consumables;
- Demonstrate integrated capability for regolith excavation and transportation required for future infrastructure development and construction;
- Demonstrate metal, ceramic, and plastic feedstock production capabilities for subsequent construction and manufacturing capabilities, needed for sustained operations;
- Systems for validation of end-to-end demonstrators for using ISRU to develop infrastructure (e.g. construction of landing pads, roads and berms, tower structures, habitation facilities, etc), but also to perform maintenance (e.g. manufacturing of parts and repair);
    - Construction involves large, not highly precise objects, that are typically not moved to other locations;
    - Manufacturing involves small, precise parts that can be moved and used elsewhere, produced in-situ partially or wholly from regolith, recycled materials/trash;

- Demonstrate increased levels of control and autonomy to minimize teleoperations and Earth supervision, targeting continuous production capability over long periods of time and also feed-forward Mars surface operations;
- Waste management as a transversal element in the ISRU value chain.

Phase 3: Sustained Lunar Operations – ISRU Objective: Large-Scale Production and Operations/Exploitation

The main objective of this phase is the full-scale production plant(s) and exploitation of lunar resources. For ISRU, there are two overarching goals for Phase 3.

- Support crew and reusable lander vehicles on the lunar surface to accomplish long term exploration goals and sustainability
- Production of propellants/reactants and consumables for missions beyond the Moon

Phase 3 starts at the point where sustainable operations have been reached. At this point in the human lunar architecture, crew and reusable lander vehicles can be supported on the lunar surface to accomplish long-term exploration goals and expansion. In this phase, the ramp-up of commercial cis-lunar transportation and ISRU propellant production has been achieved, as well as sustained surface operations at the polar region. It may also include production of propellant and consumables for missions beyond the Moon (to the Mars surface or asteroids).

Key aspects of this scenario are:

- Generate the required consumables (per specific quantitative and qualitative demand) for crew surface missions, required for sustained presence and long-term lunar exploration;
- Full-scale continuous production, storage, and transfer of cryogenic propellant for refuel of ascent, descent, and surface vehicles, required for the overall exploration strategy including Mars-forward applications;
- Full-scale ISRU systems shall produce oxygen/water (and convert water into oxygen and hydrogen) at a rate to support a minimum of one lander mission per year (TBD), maintaining a dual-path strategy of production for fuel/reactants for propulsion/energy systems and consumables for crew. Water is also critical for radiation shielding and could find applications on pressurized rovers and also on habitats;
- ISRU shall recycle waste products from human lander missions (e.g. packaging, discarded hardware, metals, plastics), recovering mass from both landed systems and crew trash, to augment resources and/or supplement ISRU industrial processes for new/additional products (e.g. plastics for regolith structures);
- ISRU systems shall support maintenance and repair of existing infrastructure, as well as construct new infrastructure for crew and surface asset protection and operational expansion;
- Waste management as a transversal element in the ISRU value chain.

The following tables 4, 5a, 5b, 5c were discussed and agreed upon by the ISECG International Architecture Working Group (IAWG) before proceeding.

Table 4: Human Lunar Exploration – Goals and ISRU Objective Overview

Phase	Goal	ISRU Objective	Descriptions	Dates	Comments	
1	Boots on the Moon in 2024	Prospecting & Demonstration In Lunar Environment	Phase 1 missions are assumed to be all robotic precursor missions up to the human landing in 2024/5. Overall objective is to obtain relevant and necessary data on resources, regolith characteristics, the environment, and hardware operation under actual lunar surface conditions to inform future ISRU architecture decisions. Demonstrations of resource utilization technologies and surface operations will start in this phase.	2024	Learning about and characterizing mare and polar region regolith and water/volatiles in shadowed regions Demonstrate ISRU concepts and functions at subscale Emphasize phased approach in decision making process. Resource utilzation technologies refers to any technology from prospecting to product storage	**Mars forward** thinking, **commercial involvement** and **international partnerships** included in all phases, based on agency priorities
2	Build up to Sustainability	Demonstrators/Small-scale Production	Phase 2 starts immediately after the boots on the ground milestone and uses a combination of robotic and crewed missions to demonstrate and verify individual elements of the integrated capabilities necessary to prove sustainable operations.	2024 to -TBD (2028)	More focus on integrated systems. Shift to increased mining perspective. Lunar architecture is aimed at demonstrating ISRU at the polar region where sustained operations will occur	
3	Sustained Exploration and Operations	Large-scale Production	Phase 3 starts at the point where we have reached sustainable operations. This means a TBD number of crew and reusable lander vehicles can be supported on the lunar surface to accomplish long-term exploration goals and expansion. Also includes production of propellant and consumables for missions beyond the Moon.	>TBD (post 2028)	On-ramp commercial cis-lunar transportation and ISRU propellant production Sustained surface operations at the polar region	

Table 5a: Human Lunar Exploration – Phase 1 ISRU Objectives

Phase	Objective #	Description	Rationale	Source(s)	Comments	Relevent SKGs
1	1	Phase 1 robotic missions shall focus on resource assessment (geotechnical/physical, mineral/chemical, and volatile) and ground-truthing of potential sites, both polar (sun-lit regolith and ice volatiles) and non-polar (regolith and solar wind volatiles).	Assess sites in both regions for comparison and final selection	GER	Locations based on agency priorities.	I.C2, C3, E1 I.D3, D4, D6, D7
	2	Data shall be collected for understanding the concentrations of minerals (eg. oxygen content, metals) and solar wind volatiles in regolith for each potential site.	Required for future design decisions (Site selection, ISRU techniques)	GER		I.C2, C3, E1
	3	Ground-truthing missions shall search for and answer questions regarding the form, composition, and depth of Lunar ice, minerals and other volatiles for subsequent phases.	Required for future design decisions (Site selection, ISRU techniques)	GER, GPoD		I.D3, D4, D6, D7
	4	Bulk hydrogen shall be measured within a minimum depth of 1m.	Required by GER	GER	Indirect and direct measurements	I.C2, D6
	5	Lunar science objectives shall be supported by ISRU precursor missions and vice versa to the maximum extent possible.	Maximize common objectives, instruments, and measurements between science and resource prospecting goals	GER, GPoD		I.C2, C3, D3, D4, D5, D6, D7, E1 III.B2, C2, E
	6	Landers/Rovers/Orbiters shall provide the capability to measure and map terrain features.	Required for future design decisions (Site selection, ISRU techniques)	GER, GPoD		I.D4 III.B2, B3
	7	Data shall be collected for understanding lunar regolith and dust properties and demonstrate mitigation techniques for long-term surface operations including radiation/micrometeriod shielding mateials and concepts	Understanding regolith/dust properties and demonstrating mitigation techniques for long term operation of all surface assets will be critical			I.D3, D4, D5 III.C2, D1, D4, E1, G1, H1
	8	Ground-truthing missions shall provide data to refine orbital measurements and environment models.	Required for future design decisions (Site selection, ISRU techniques)	GPoD		I.B2, C2, C3, D4, D6, D7, E1
	9a	Precursor missions shall demonstrate oxygen extraction from regolith capability.	Individual capability demonstrations should start in phase 1 to let phase 2 focus on integrated systems.		Oxygen extraction from regolith may require multiple steps and each step may be demonstrated or not as part of the oxygen extraction demonstration. Demonstrations may occur anywhere on the lunar surface	I.G1 III.A5, A6, D1
	9b	Precursor missions shall demonstrate polar water (and volatiles) extraction and capture capabilities. Also, demonstrate water/volatile cleaning techniques required for subsequent processing or users	Individual capability demonstrations should start in phase 1 to let phase 2 focus on integrated systems.		Within or outside of PSRs	I.G1 III.A1, A2, A3, A5, A6, D1
	9c	Precursor missions shall demonstrate regolith processing capabilities to extract metal and other product	Individual capability demonstrations should start in phase 1 to let phase 2 focus on integrated systems.			I.G1 III.A5, A6, D1
	10a	ISRU systems shall demonstrate regolith excavation and comminution capabilities (performance, operation, life/wear)	Individual capability demonstrations should start in phase 1 to let phase 2 focus on integrated systems. (Regolith excavation requirements different from transportation requirements)		Extraction methods include: bucket wheel, auger/drill, scoop, pneumatic Comminution includes crushing, size sorting, and mineral beneficiation Operation and control of actuators (autonomous, manual, supervised autonomy)	I.G1 III.A1, A3, A4, A6, D1
	10b	ISRU systems shall demonstrate regolith transportation capabilities.	Individual capability demonstrations should start in phase 1 to let phase 2 focus on integrated systems. (Regolith excavation requirements different from transportation requirements)			I.A2, A6, B3, C1, C2
	11	Phase 1 missions shall validate Phase 2/3 ISRU payload designs.	Required for future design decisions (Site selection, ISRU techniques)	GER		III.A1, A2, A3, A4, A5, A6, C2, D1, D4, F1, F2, F3, F4, F5, G, H

Table 5b: Human Lunar Exploration – Phase 2 ISRU Objectives

Phase	Objective #	Description	Rationale	Source(s)	Comments	Relevent SKGs
2	1	Required Lunar ISRU capabilities and technologies will be demonstrated and used as a proving ground for Lunar Sustainability and preparation for human Mars exploration	Required for system validation and growth for sustainable operations	GER	Being done based on agency priorities for Mars forward and commercial advancement	III.A1, A2, A3, A4, A5, A6, C2, D1, G, H
	2	Grade and quantity of ice water deposits shall be measured and mapped.	Required by GER	GER	This is aimed at defining water and volatile resources to select sites and plan for extraction operations	I.D6
	3a	ISRU systems shall demonstrate integrated systems for the mining and production of water from Polar craters/regions	Integrated system validation. Less risk using regolith, but water mining more beneficial for refueling scenarios	GER, GPoD		*I.D3, D4, D5, D6, G1 (Covered in Step 1)* III.A1, A2, A3, A5, A6, C2, D1, F2, F4
	3b	ISRU systems shall demonstrate integrated systems for the mining and production of oxygen from regolith.	Integrated system validation. Less risk using regolith, but water mining more beneficial for refueling scenarios	GER, GPoD		*I.C2, E1, G1 (Covered in Step 1)* III.A1, A2, A3, A4, A5, A6, B3, C2, D1, F1, F3
	4	ISRU systems shall demonstrate the liquefaction, storage, and transfer of consumables.	Tech demo and validation for ISRU-derived propellants, crew consumables, and/or fuel cell reactants	GER		III.E5
	5a	ISRU systems shall demonstrate the process of converting and liquefying hydrogen and oxygen from water	Demonstration of water-based cryogenic propellant capabilities.	Lunar ISRU Strategy Slides		
	5b	Small scale ISRU systems shall demonstrate the use of water or conversion of water into oxygen and hydrogen for life support and regenerative power capabilities	Demonstration of water for crew usage and conversion for regenerative fuel cells for operating and/or surviving during lunar night or sustained periods of darkness			
	6	ISRU systems shall demonstrate integrated capability for regolith excavation and transportation.	Required for future infrastructure development and construction, and possibly relocation	GER, GPoD		III.A1, A2, A6, B3, C2
	7	ISRU systems shall demonstrate metal, ceramic, and plastic feedstock production capabilities for subsequent construction and manufacturing capabilities	In situ derived feedstocks will be needed for sustained operations for construction and manufacturing			III.A5, A6
	8a	ISRU systems shall demonstrate the ability to use ISRU for infrastructure development (eg construction of landing pads, paths, facilities...).	Tech demo and system validation	GER	Construction involves large, not highly precise objects, that are not typicallty moved to other locations	III.A5, A6, G, H
	8b	ISRU systems shall demonstrate the ability to use ISRU for maintenance (manufacturing and repair).	Tech demo and system validation	GER	Manufacturing involves small, precise parts, that can be moved and used elsewhere. ISRU systems involve use of partially or wholy produced in-situ from regolith, recycling, trash, etc.	
	9	ISRU systems shall demonstrate increased levels of control and autonomy to minimize tele-operation and Earth supervision for sustained and future Mars operations	Capability will be required for continuous production operations over long periods of time and for Mars surface operations with significant communication time delays			III.A6, B3

Table 5c: Human Lunar Exploration – Phase 3 ISRU Objectives

Phase	Objective #	Description	Rationale	Source(s)	Comments	Relevent SKGs
3	1	ISRU systems shall generate required crew consumables (per specifications and amounts) for crew surface missions.	Required for sustainable presence and long-term Lunar exploration	GER		
	2	ISRU systems shall be capable of continuously making, storing and transferring cryogenic propellant for refuel of ascent, descent and other vehicles on surface.	Required for overall exploration strategy, (Mars forward)	GER		
	3	If the preferred pathway is processing of lunar regolith, ISRU systems shall produce oxygen at a rate to support a minimum of one lander mission per year as an initial production capability.	Dual path strategy, oxygen production for consumables and propellant	Lunar ISRU Strategy Slides		
	4	If the preferred pathway is extracting water from polar craters, ISRU systems shall produce water at a rate to support a minimum of one lander mission per year as an initial production capability.	Dual path strategy, water production for consumables and propellant	Lunar ISRU Strategy Slides		
	5	ISRU systems shall recycle waste products from the human lander missions (e.g., packaging, used hardware, metals, plastics)	Recovering mass from landed systems and human mission trash may augment resources and/or supplement ISRU industrial processes for new/additional products (e.g. plastics for regolith structures). Recycled masses would reduce amount of material needed to be removed from the living environments/locale.			
	6	Full scale ISRU systems shall produce water or convert water into oxygen and hydrogen for life support, radiation shielding, and regenerative power capabilities	Water is critical for life support, radiation shielding with possible applications on pressurized rovers and habitats, and regenerative power systems.			
	7	ISRU systems shall support maintenance and repair of existing infrastructure.	Required for sustainable presence	GER, GPoD		
	8	ISRU systems shall manufacture new infrastructure for crew and surface asset protection and opeational expansion.	Required for sustainable presence	GER, GPoD		

Human Mars Surface Exploration

Since human lunar exploration is a stepping-stone to future human exploration of the Mars surface, the ISRU Gap Team believed that it was very important to assess how lunar ISRU could reduce the risk, cost, and development schedule of technologies and capabilities for Mars ISRU as part of the ISRU Gap Assessment. While the international Global Exploration Roadmap considers human exploration of the Mars surface as a major goal for ISECG members, the mission architecture and technologies for this endeavour have not been studied and defined to the same extent as human lunar missions have. Therefore, to perform an analysis of lunar ISRU for Mars mission applications, the team researched recent human Mars exploration architecture studies with the view to define a similar phased exploration approach as is currently being considered for the Moon, as described in the preceding sections. The ISRU Gap Team utilized the following studies and papers] in the assessment:

- "Sustaining Human Presence on Mars Using ISRU and a Reusable Lander", AIAA 2015-4479 [3]
- "Frontier In-Situ Resource Utilization for Enabling Sustained Human Presence on Mars," NASA Technical Report, NASA/TM-2016-219182 [4]
- "Hercules Single-Stage Reusable Vehicle supporting a Safe, Affordable, and Sustainable Human Lunar & Mars Campaign", AIAA 2017-5288 [5]
- "Mars Base Camp: An Architecture for Sending Humans to Mars," New Space Vol. 5, No. 4 [6]
- Affording Mars V, "Scenarios for Achievable Human Missions to Mars: Comparison Among Architectures" [7]
- Affording Mars VI, "The Sixth Community Achievability and Sustainability of Human Exploration of Mars Workshop" [8]
- Affording Mars VII, "The Seventh Community Workshop for Achievability and Sustainability of Human Exploration of Mars" [9]

A major outcome of this analysis was the definition of four distinct development Phases that captured the progressive build-up of relevant ISRU systems capability for the Mars scenario.

Phase 0: Preparatory Missions

Phase 0 designates activities corresponding to robotic Mars missions (recent, on-going, and planned) that will provide critical information about the Mars surface and subsurface, potential resources, and test technologies relevant to the progressive deployment of ISRU applications. At this time, only one ISRU technology demonstration is manifested for operation on Mars, namely the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) for oxygen production from atmospheric carbon dioxide. Unless other ISRU resource assessment and extraction and/or ISRU technology demonstrations are developed and flown, Phase I ISRU will most likely be limited to Mars atmosphere resources for mission-critical applications. Affordable Mars V "Towards Permanent Habitation" Scenario 3 offers a Phase 0 mission campaign designed to provide the critical information sought before committing to a particular human landing site. The multiphase approach described in the NASA/TM [RJ(RP3] depends on site selection with ISRU in mind from the start and therefore provides important reference information for this development Phase.

Table 6a. Human Mars Architecture and ISRU Objectives – Phase 0

Relevant Current/Planned Missions	Relevance-ISRU Architecture	ISRU Resources - Knowledge	ISRU Products
Mars Reconnaissance Orbiter	• HiRISE camera • CRISM spectrometer • SHARAD penetrating radar	Global understanding of resources and terrain	
Mars Express	• HRSC (High Resolution Stereo Camera) • OMEGA (Visible and Infrared Mineralogical Mapping Spectrometer) • MARSIS (Sub-surface Sounding Radar Altimeter)	Global understanding of resources and terrain	
Mars Curiosity Rover	• Drilling • Mineral assessment • Volatile assessment of samples	Water in soil/hydrated minerals	Water
Mars Perseverance Rover	• Sample collection, mineral assessment • MOXIE demonstrator technology validation • RIMFAX ground-based radar subsurface imager	Carbon Dioxide in Atmosphere	Oxygen
ExoMars Rover	• Drilling and soil sampling to a depth of 2 metres. • Subsurface assessment (GPR) • Mineral assessment • Volatile assessment of samples	Water in soil/hydrated minerals	Water
MMX - Martian Moons Exploration	• TENGOO (TElescopic Nadir imager for GeOmOrphology) • OROCHI (Optical RadiOmeter composed of CHromatic Imagers) • LIDAR (Light Detection And Ranging) • MIRAS (MMX InfraRed Spectrometer) • MEGANE (Mars-moon Exploration with GAmma rays and NEutrons) • CMDM (Circum-Martian Dust Monitor) • MSA (Mass Spectrum Analyzer) • Sampler and Sample Return Capsule	Mars moon map of hydrated minerals and terrain Correct samples from Martian moon and bring samples back to the Earth	

Phase 1: Pre-Outpost

Phase 1 describes the “Boots on Mars” stage that would involve one or more short-term human exploration and return missions. It corresponds to Affording Mars V (AM-V) Scenario 1, the AIAA “Prior to ‘Prepare’ Phase”, and

"Mars Base Camp". During this phase, infrastructure buildup at a single location would most likely occur, allowing subsequent human missions to explore with greater capabilities and distances. Resource assessment of water resources and subsequent extraction and processing demonstrations and operations would occur in this phase if not already performed in Phase 0, until mission planners have sufficient confidence to utilize in mission-critical operations, such as crewed ascent. Demonstrations associated with in-situ manufacturing and construction may also be performed during this phase in preparation for Phase 2.

Table 6b. Human Mars Architecture and ISRU Objectives – Phase1

Mission Architecture	ISRU Resources	ISRU Products
Placing the initial uncrewed infrastructure in low-Mars orbit, in high-Mars orbit, and on the Martian surface, for navigation, communication, space weather, site selection, and ending with a sample return mission that also supports scientific investigations.	Mars Atmosphere: carbon dioxide primarily but possibly argon and nitrogen as well Multiple sources of water: granular soil (1-3 wt%), hydrated minerals (up to 10 wt%), and subsurface ice	Oxygen, possibly for crewed ascent propulsion Water (for non-critical mission use initially) Possible conversion of water/CO2 into methane and other hydrocarbon products (depends on results from Phase 0) Possible manufacturing and surface civil engineering and construction demonstrations.
Phase 1 stages (AM-V Scenario 3 ConOps): **a. Commercial launches, direct to Mars** **b. One low-Mars orbit optical / synthetic aperture radar spacecraft survey** **c. Two high-Mars orbit navigation / communications / space weather spacecraft**		

Phase 2: Outpost Start

The goal of **Phase 2** is to support the "build-up to sustainability". This phase would correspond to the AM-VI and AM-VII expansions on the AM-V Scenario 2 ("Outpost"), and roughly aligns with the "Prepare" phase of the AIAA report and NASA/TM and the intermediate and latter missions within the comprehensive campaign of AM-V Scenario 3 ("Towards Permanent Habitation"). Developing the surface and orbital infrastructure to provide for longer duration human presence would be a priority to support the Phase 2 goal. The importance of ISRU capability becomes particularly apparent as the use of local resources would be a critical limiting factor on further mission developments.

Table 6c. Human Mars Architecture and ISRU Objectives – Phase 2

Mission Architecture	ISRU Resources	ISRU Products
Establishing an initial orbiting base about Mars where crew may safely conduct further surveys of the human exploration zone (EZ) as needed and assist via teleoperations the build-up of surface assets once the resources and hazards are verified.	Mars Atmosphere: carbon dioxide, argon, and nitrogen Water from one or more sources: granular soil (1-3 wt%), hydrated minerals (up to 10 wt%), and subsurface ice Mars soil, minerals, and metals	O2 for propulsion, fuel cells, and crew CH4 for propulsion and fuel cells Water for crew, radiation protection, manufacturing and construction N2 and Ar for life support buffer gases, science, and inert gas needs Trial amounts of manufacturing and Construction feedstock: modified soil, metals, plastics Manufacturing and construction demonstrations
Phase 2 Stages (AM-V Scenario 3 ConOps): **a. Mixture of SLS and commercial launches, cislunar aggregation** **b. Initial habitation infrastructure in Mars orbit** **c. First crews to Mars orbit, with potential first visits to the EZ anticipated to be short stays in pressurized rovers.**		

Phase 3: Sustained Presence

The goal of **Phase 3** is to support "sustainable exploration" on the surface of Mars. It would go beyond the AM-V Scenario 2 ("Outpost") and Scenario 3 ("Towards Permanent Habitation"), and effectively align with the "Found" and "Expand" phases of the AIAA report and NASA/TM and the latter missions within the comprehensive campaign of AM-V Scenario 3 ("Towards Permanent Habitation"). Reliable, predictable exploitation of Martian resources would now be essential to mission success.

Table 6d. Human Mars Architecture and ISRU Objectives – Phase 3

Mission Architecture	ISRU Resources	ISRU Products
The initial build-up of surface assets to support a crew, including the insertion of the initial surface crew upon verification of operational safety metrics for the surface systems.	Atmosphere: CO_2, N_2, Ar Water Minerals/metals	O2 for propulsion, fuel cells, and crew CH4 for propulsion and fuel cells Water for crew, radiation protection, manufacturing, and construction N2 and Ar for life support buffer gases, science, and inert gas needs Production amounts of manufacturing and Construction feedstock: modified soil, metals, plastics Construction of berms, landing pads, and structures Manufacturing of spare parts from in-situ plastics and metals (from in-situ and recycled materials)
Phase 3: (AM-V Scenario 3 ConOps) **a. Mixture of SLS and commercial launches, cislunar aggregation** **b. Initial surface infrastructure at verified landing site** **c. Crews to the Martian surface for short stays in a habitat at verified landing site, assisting in infrastructure buildup.**		

ISRU Resources, Products, and Applications

Table 7 below links in-situ Resources to Products, and Products to their Applications. The upper rows are dedicated to Resources, with the heading on the left. Rows in the lower half refer to Users/Applications and have the heading on the right. The headings for Product, which occupy the columns, are in the middle and are shared between Resources and Applications.

The table inputs are based on impact (colour), i.e., the importance of the resources and products for achieving sustained human operations or on mission architecture; and timeframe (letter), i.e., the priority or need for the product as a function of insertion into the human exploration architecture. As mentioned before, lunar architecture was based on the GER and Artemis program. For Mars, impact on mission architecture and timing was based on the 3 phased approach for human lunar exploration and the human Mars mission architecture (Accessible Mars V, VI, and VII).

Resources were categorized into Moon-specific resources, dived into Equatorial and Polar, resources generated by the crew, and Mars-specific resources. Resources that had a too broad application were not being considered by international players or that were a product in itself were not covered in this table. For example, despite extended sunlight being an important resource, a prerequisite for exploration location, and applicable to all ISRU products, it was not included in the table. Moreover, caves with access via skylight may be important and can be considered a resource, but were not covered in this table. To the knowledge of the ISRU team, helium-3 is not being considered as a resource for sustained lunar surface operations because of its scarcity and lack of space application. KREEP (potassium, rare earths, phosphate) and radioisotopes are included but are currently being investigated as a resource mainly by the private sector. It should also be noted that in-situ-derived radioisotopes are expected to have low impact on the architecture for electrical power generation. The evaluation for crew-generated resources was created with Human Lunar Exploration. A specific section for Mars resources and possible Mission/Architecture impacts was included to provide consideration of technology selections that might be applicable to Mars, but crew-generated resources were not evaluated specifically for the Mars crew/architecture.

ISRU products have a level of complexity that could not be delivered in the table. Indeed, products can either come directly from a resource or be produced from resources during processing, or multiple resources might be needed to create a product. Moreover, products coming from different sources can have specific applications, and therefore require different processing and storage technologies. For example, Water and Oxygen include resources needed for both human consumption and other uses, but the purity required for each use is different. A higher level of detail was given for Nutrients required for direct crew consumption and plant growth since these two technologies have different timeframes. Moreover, non-metallic materials produced from regolith were divided into Ceramics and Construction material (major constituent is bulk or modified regolith, with less than 30% binders/additives).

Applications were subdivided into Energy Sources, Life Support, and Construction and Manufacturing. Construction includes applications where large, not highly precise objects that are not typically moved to other locations are produced. Manufacturing, instead, was defined as those activities that fabricate small, precise parts that can be moved and used elsewhere. Despite being highly important for propellant, water was not associated with Propulsion, since it is not a propellant itself for human propulsion systems. It should be noted that radiation shielding was difficult to fully assess. At this time, the human lunar mission assessments and studies have been primarily limited to 42-day surface stays or less. Therefore, mitigating long-term exposure to solar radiation, Solar Particle Events (SPEs), and especially Galactic Cosmic Radiation (GCR) has not been fully addressed by mission planners. It is expected that either the impact or the timeframe of different materials might change as more information is gathered.

To understand how to utilize the table, readers should consider first examining the top of the table, which evaluates the resources available versus the products that can be produced from them. The table allows the reader to focus their attention on “green” (‘high impact’) resource-products as well as those that can be used “near-term” (‘N’) as well as understand what early work may be required to enable mid and longer-term products. The top of the table shows that Highland regolith, polar ice, and residual propellant after landing are “high impact”/”near-term” resources that can enable mission consumable products such as water, oxygen, and hydrogen, and bulk material for construction and manufacturing. Readers should than look at the lower half of the table where products produced are now matched with potential applications and use cases. Again, the reader is encouraged to look at “high impact”/”near-term” (‘green’/’N’) mapping as well as mid and longer term products and their impact on different mission applications. The bottom of the table shows that propulsion, fuel cell power, and life support applications benefit the most with early development ISRU products.

Table 7. ISRU Resources, Products, and Applications

ISRU Resources			Water	Oxygen	Propellant/ Reactants (Fu & Ox)	Thermal/ Energy Storarge	Construction Materials/ Feedstock	Ceramics	Metals	Plastics/ Polymers	Repurpose Hardware	Crew Nutrients/ Non-plant Food	Plant Growth/ Nutrients
Moon Resources	Equatorial	Mare Regolith		M	M	L	M	L	L				L
		KREEP (K, Rare Earth Elements, P)							M				L
		Radioisotopes (thorium, uranium)				L							
		Pyroclastic Glasses	M	M	L	L	L	L	M	L			
		Solar Wind Volatiles (H, C, N)	L		L					L			L
	Polar	Highlands Regolith		N	N	M	N	M	M				L
		Polar Ice (H_2O) - H_2 and/or O_2 Source	N	N	N		L			L		L	L
		Cold Trapped Volatiles (not H_2O)			M					L			L
Crew-Generated Resources		Solid Trash/Crew Waste (not ECLSS)	M	M	M		L		L	N			M
		ECLSS Gas Waste (CO_2, CH_4)		M	M					M			N
		ECLSS Solid Waste	N		M		M			N			L
		ECLSS Liquid Waste	N		M		M			N		M	M
		Residual Prop from landers	N	N	N								
		Spent landers (crew, cargo, robotic)							L	L	L		
		Obsolete/Unrepairable Equipment						L	L	L	L		
Mars Resources		Mars Atmosphere (CO_2, N_2, Ar, other)		N	N					L		M	L
		Regolith/soil		L	L	L	M	L	L				L
	Water Resources	Granular low-H_2O% soil	M	M	M		L					M	L
		Hydrated minerals	M	M	M		L	L	L			M	L
		Subsurface ice sheets	M	M	M		L			L		M	L

Applications		Water	Oxygen	Propellant/ Reactants (Fu & Ox)	Thermal/ Energy Storarge	Construction Materials/ Feedstock	Ceramics	Metals	Plastics/ Polymers	Repurpose Hardware	Crew Nutrients/ Non-plant Food	Plant Growth/ Nutrients
Energy Sources	Propulsion (propellants): Ascent, Hoppers, Reusable Landers		N	N								
	Regenerative Fuel Cell Power (reactants): Stationary, Mobile	M	M	M								
	Nuclear power system - From Earth	N				N						
	Nuclear power system - From ISRU				L							
	Thermal Control	M			M	M	M	L	L			
Life Support	Consumables for operation of hardware: EVA, Hab., Press. Rover	M	M									
	Edible Biomass/Food										M	
	Plant growth											L
Construction & Manufacturing	In Situ Manufacturing and Repair	L				M	M	M	N			
	Crew Radiation Shielding (Habitat)	N				N	L	L	M			
	Crew Radiation Shielding (Mobile)	N					M		M			
	Construction: pressurized and unpressurized structures	L				M	M	M	M	L		
	Surface Stabilization: Landing Pads/Roads/Berms	L				N	N	M	M			

		Lunar Exploration	Mars Exploration
Impact	High Impact	Important for initial sustained operation at the lunar polar region	Strongly influences mission architecture (pull)
	Medium Impact	Important for longer-term sustained operations or for non-polar regions	Impacts mission architecture, requires some infrastructure (buildup)
	Low Impact	Limited importance to area of ISRU	Limited impact on mission architecture
	Not applicable	Not applicable	Not applicable
Time-frame	N = Near Term	During Build up to Sustainability	Predeploy or 1st Mars human surface mission
	M = Medium Term	At Start of Sustainability	2nd to 4th Mars human surface mission
	L = Long Term	During and later in Sustainability Phase	Long-term sustained Mars surface outpost

TECHNOLOGY ASSESSMENT

The purpose of the Technology Assessment in this Report (in Appendix B) is to provide program/project teams with a capability assessment and identification of recent, on-going, and approved development of technologies for ISRU. General Issues/Needs and Agency/National capabilities were defined for each ISRU SKG Theme. Specific Current Technology Work was assessed by individual Space Agency. The content of the Appendix B. Technology Assessment Table is an on-going effort and is intended to help identify: 1) technology areas under focus by each agency, and 2) potential expertise in specific ISRU areas by different space agencies/countries. All the contents are therefore not meant to be taken as final or all-inclusive, but represent an effort of the team to give management and readers the tools to understand the scope and direction for on-going and future technology and system development activities.

<u>ASA/CSIRO – Australia</u>

Australia's historical research and development with regard to space-related technologies have been largely focused on radio-astronomy and communications support for international space missions. This work has primarily been supported by the national science agency, the Commonwealth Scientific and Industrial Research Organisation (CSIRO). More recently, however, the Australian Space Agency (ASA) has initiated a program of development across a range of space-related domains that includes a strong focus on ISRU and other support services. Australia's world-class capabilities in terrestrial mining are being leveraged to develop new ISRU-related technologies in the areas of sub-surface sensing, autonomous vehicle navigation and control, resource transport, remote operations, and real-time materials characterisation.

<u>ASI – Italy</u>

At present, ASI is mainly contributing to ESA Exploration missions focusing on technology research and developments in scientific payloads for surface and subsurface characterization (e.g. ExoMars drilling system and spectrometer, technologies related to extracting oxygen from regolith on the lunar surface), which surely represents an essential phase for any future ISRU activity. Researches funded by ASI address also the radiation shielding topic, aiming at developing wearable radiation protection devices for future human explorers. Supported by private or other public funding, technology developments at national level for future lunar ISRU activities involve also sampling/excavations tools and regolith handling systems.

<u>CNES – France</u>

At CNES, an Exploration technology roadmap is currently updated. The aim is to prepare our industry to be competitive for contribution to International programs. The ISRU activity is a new area at CNES, but we have experience on technologies that could be useful in the global ISRU loop as: Autonomous Rover Navigation software, Sample analysis.
In 2020, we have started a technology roadmap exercise on some critical technologies among the list of the GER Critical Technology needs. Those workshops are organized at French level with: CNES Expert, Industry Expert and Research/Academic Experts. The aim is to identify technologies in areas which France could work on and increase the TRL to be competitive for futures activities via a "niche" approach. For ISRU, we will focus on applications for the regolith: gas extraction/purification/storage and the 3D printing of small tools for astronauts. We will also participate to the ESA activities for ISRU via various channels of French funding.

<u>CSA/NRCan – Canada</u>

Canada has been involved in ISRU related technology development for many years. Recent developments focus on mobility-related technologies and payloads for scientific objectives and ISRU. For instance, the CSA is currently pursuing its rover development on smaller micro-rover size vehicles (~30 kg) but is also considering future potential contribution of or to larger medium-size utility vehicles and human unpressurized or pressurized rovers. In addition to mobility systems, CSA is also carrying on manipulator and instrument developments such as multi-spectral spectrometer, neutron spectrometer, Lyman Alpha, Integrated Vision Systems, and related geophysics and volatile characterization devices. Opportunities for flying such technologies are considered as part of the on-going 5 years Lunar Exploration Accelerated Program (LEAP).

DLR – Germany

DLR within research and development in general, as well as other major research institutions such as the German Research Centre for Artificial Intelligence, have a focus on autonomy and telerobotics, considering ISRU as important mission-specific vital payloads. Research funded by EU, ESA, and national sources addresses ISRU topics such as 3D printing, instrumentation, as well as volatile extraction and building with regolith, typically together with additional partners.

ESA – Europe

In ESA, technology for Exploration is defined, planned, developed, and implemented for specific missions. There is also a generic component of technology development pertinent to support all ESA missions. The ISRU field has recently emerged but it has been growing at a fast pace in ESA. Two payloads are currently under development in the area of ISRU for missions of opportunity, the PROSPECT payload (currently in the implementation phase) and the ISRU-Demonstration Mission (ISRU-DM) payload (currently in the definition phase).
PROSPECT includes a drill, the analytical instrument, and the Solids Inlet System (a carousel of ovens and sealing system, in which heating to release gases and ISRU proof-of-concept reactions takes place). The experimental ISRU proof-of-concept will demonstrate the hydrogen reduction reaction on lunar regolith.
The ISRU-DM payload aims at collecting and delivering a sample of lunar soil into an electro-chemical reactor with the objective to extract oxygen directly from the regolith. Depending on the electro-chemical process used in the reactor, metal alloys could also be produced as a by-product.

Based on the ESA Space Resources strategy defined in 2019, the ESA ISRU campaign roadmap has been recently elaborated and it includes a broad set of technologies for each specific area in the ISRU value chain. The ESA ISRU campaign roadmap has largely provided the basis for the content of the technology portfolio captured in this ISECG report, but which also includes generic technologies applicable to ISRU missions.

JAXA – Japan

JAXA will focus on four strategic technology fields by specifically utilizing Japan’s expertise in manned and unmanned space technologies accumulated through experiences with the ISS and other scientific explorations. The four fields include the deep space cargo resupply technology, human habitation technology in deep space, technology for landing-to / taking-off-from gravitational celestial body, and sustainable surface exploration technologies, especially lunar polar exploration to be followed by the development of manned pressurized rover.

KARI/KICT/KIGAM – South Korea

In Korea, no specific ISRU mission has been defined so far but strategic planning and roadmap activities, as well as ISRU research and infrastructure, have been actively performed among Korean communities since ISRU research activities were initiated in the mid-2010s. KARI is working on prototyping environmental control and life support systems prospectively used for lunar bases in the future. KIGAM focuses on the development of lunar resource prospecting technology including surface imaging and mineralogy. Gas extraction methodology from lunar simulants has recently launched with the strong basement of KIGAM’s intrinsic legacy on mining and resource collection/separation capabilities and facilities. The scientific payloads such as X-ray, Gamma-ray/Neutron spectrometers, LIBS, etc., and associated resource evaluation technologies for resource prospecting and assessment are currently under development in the level of development model or flight model by KIGAM and other institutions.

KICT has mainly focused on resource prospecting/excavation and civil engineering and surface construction technologies associated with simulated planetary environments. Not only unmanned geospatial information modelling is ready for prospecting ground test with lunar rover prototype in real-time based on stereo cameras, but unmanned subsurface drilling investigation for icy soil deposits on extraterrestrial local construction site. As for lunar surface construction area, production technology of physically and chemically (Nano-phase Fe) mimicked lunar simulants, micro-wave sintering, and solidification of the lunar simulants are evaluated aiming at over TRL 5.

<u>LSA – Luxembourg</u>

The Luxembourg Space Agency is itself not active in the development of ISRU technology but supports the activities of several commercial entities, of public research institutes, as well as of the European Space Resources Innovation Centre (ESRIC), developed in partnership with ESA.

<u>NASA – USA</u>

Technology development for ISRU is primarily the responsibility of the Space Technology Mission Directorate (STMD) within NASA. Within STMD ISRU resource processing technologies fall under the In-Situ Propellant and Consumable Production (ISPCP) project. Excavation and surface construction technologies fall under the Advanced Materials, Structures, and Manufacturing (AMSM) project. Resource assessment technologies are the responsibility of the STMD ISPCP project and NASA's Science Mission Directorate. Since multiple surface assets are required for scientific and human exploration of the lunar surface, STMD initiated the Lunar Surface Innovation Initiative (LSII) which covers technology development for six major surface exploration aspects: ISRU, Surface Excavation and Construction, Sustainable Power, Lunar Dust, Extreme Access, and Extreme Environments.

STMD has includes a broad range of programs, known as the Technology Pipeline, which allow for requests for technology development from the extremely low Technology Readiness Level (TRL) all the way to flight demonstrations. A detailed Strategic Technology Plan for ISRU, which includes an assessment of current technology readiness levels and gaps, is in work and expected to be released in 2021.

<u>UAESA – United Arab Emirates</u>

The UAE Space Agency is currently not active in the development of direct ISRU technology. But, currently support related activities that could contribute to ISRU indirectly, such as autonomous robotics systems and delayed teleoperations.

<u>UKSA – United Kingdom</u>

The UK Space Agency contributes to ESA's Exploration Envelope Programme where we take part in a variety of missions and support a number of technologies that will be relevant to ISRU. The UK's main focus is on the fundamental technologies and background science that will enable further exploration of our solar system and ISRU is rapidly becoming an important part of that. The Agency has funded the research and development of robotic systems, autonomous navigation, remote mapping technologies, and more that will support ISRU endeavours. We are also supporting early TRL technology with a direct impact on ISRU including methods for extracting oxygen and metals from lunar regolith with a view to supporting future ISRU demonstration missions.

TEST FACILITY ASSESSMENT

The scope of the Facility Assessment in this Report is primarily dedicated to facilities that can accommodate regolith for environmental and operational testing. Other facilities that can simulate relevant space environments for testing of ISRU technologies are also included.

The list is broken down into two main sections: planetary surface environmental simulation facilities and ambient test/analogue facilities for operational development. While there are numerous 'natural' analogue facilities around the world that are utilized for science instrument and operational testing, those facilities/locations were not included in this assessment. Instead, human-created analogues and environmentally controlled ambient test facilities were covered. The planetary environment simulation facilities considered in this section are further subdivided into 4 size categories:

- Research/Component level (<1.2 m/4ft diameter);
- Component/ Subsystem level (1.2 to 4.25 m/4 to 14 ft diameter);
- Subsystem/System level (4.25 to 7.62 m/14 to 25 ft diameter); and
- Large System level (>7.62m/25 ft diameter).

An effort was made to also provide the readers with relevant environmental capabilities (Temperature, Vacuum, etc.) and contact details.

The Facility Assessment list is not all-inclusive, but comprises those facilities that are currently or could be used for testing of ISRU technologies, and are known by each Agency to be suited for the purpose. In particular, it is expected that numerous additional Research/Component level environment simulant chambers/bell jars exist since the cost of purchasing and operating these chambers is very low. Each space agency/country included facilities that they deemed important to note as part of their ISRU development efforts.

<u>ASA/CSIRO – Australia</u>

Australia has a number of test facilities that can support the development of ISRU-related technologies, including the Advanced Instrumentation and Technology Centre at the Australian National University (ANU). This centre houses the Wombat XL Space Simulation Facility, which is a cleanroom environment that supports vacuum, thermal, vibration, and shock testing. The CSIRO has also developed a non-vacuum testbed for early-stage ISRU technology development and testing. However, no dusty vacuum chamber facility exists at this stage in Australia.

<u>ASI – Italy</u>

The Italian facilities list reported in Table 8 is based on an ASI assessment of those relevant structures that are planned or are feasible to be used for on-going and future ISRU technology development efforts.

Following the Italian involvement in European and international Mars-oriented exploration missions, many efforts have been invested in the last years by private companies, also with the support of ASI's funds, in the development or upgrade of ambient simulation facilities. These facilities aim to simulate the features of the extraterrestrial environment (e.g. morphology, surface compactness, light and temperature conditions) and are mainly devoted to develop and test robotic systems or to validate surface operations. Small to medium dirty thermal vacuum chambers are already available at the national level to test and verify the performance of components in representative dusty planetary environments (lunar or Martian) under variable temperature and pressure conditions. Specific small-sized ISRU-oriented facilities, designed to investigate and validate specific technologies or to simulate specific dusty conditions, are currently available or are under development mostly by national Universities and research centres and, following the growing institutional interest on the ISRU topic, a detailed survey of all these capabilities is planned soon by ASI.

CNES – France

CNES is highly interested in working on ISRU activities but it does not possess related test facilities internally. As result, the list includes only external facilities that are known to support ESA, French Industry, and on-going CNES-funded ISRU technology development activities. Two facilities are mentioned: ONERA-DROP (for Plasma tests) and COMEX chamber (for dirty tests with Regolith).

CSA/NRCan – Canada

In Canada, efforts have been deployed over the last five years to enhance the capability in terms of Dusty Thermal Vacuum (DTVAC) chamber. A new DTVAC is being delivered and will be operated from the CSA David Florida Laboratory (DFL) situated in Ottawa in 2021. The test volume of the chamber is up to $0.9m^3$. The facility is also equipped with a distribution system for regolith as well as cooled down with liquid nitrogen (LN_2) with chamber diameter of 1.5 m for a length of 1.5 m. It is also possible to cool down the platen using liquid helium (LHe) down to 41k. Characteristics of the chamber are provided in Table 8. This chamber will be an addition to the standard TVAC larger chambers available at DFL. In addition to chambers, the CSA and the Canadian industry and academia also have a number of smaller facilities to characterize and test sub0-systems and components, a dusty TVAC mount has also been developed to host a rover drivetrain for testing a few years ago. The CSA also has its analogue terrain available for mobility testing as well as a large number of analogue sites and quarries that have been used to test hardware throughout the years.

DLR – Germany

Major facilities are included in the list of facilities of this report. Many other facilities are typically based in individual laboratories and may not be ISRU specific. Industry operates small ISRU laboratories as well. The LUNA facility in Cologne, see below, shall be operated bilaterally by DLR together with ESA.

ESA – Europe

The capability list presented includes a variety of test facilities that range from small (component level) to medium (sub-system level) to large (system level) volumes and associated representative environment conditions for testing ISRU technologies. Some of the ESA Exploration programme Member States are considering plans to expand their existing capability (e.g. Denmark) or create a new one (e.g. Luxembourg) and that is proof of ESA's interest in ISRU.

The LUNA Analogue Facility at the ESA-EAC centre in Germany, is planned for construction and outfitting in 2021 and will be used in the scope of operational concepts. The following aspects will be addressed: solar illumination simulation of various lunar environments (polar and equatorial), flexible terrain modelling, gravity offloading, human, robotic, and cobotic operation concepts, a dedicated dust, and separate gas laboratory. Additionally, an attendant to LUNA will be an analogue surface habitat facility (FlexHAB) - this facility will also contain representative elements for a stand-alone power system based on fuel cells, batteries, and photovoltaic panels.

JAXA – Japan

The listed table shows JAXA's test facilities related to ISRU. The two chambers located at Chofu Aerospace Centre are utilized for dust dispersion mechanism and simulated lunar surface under vacuum conditions. Since 2017, the new large-scale test facilities located at Sagamihara Campus have become in operation for space exploration experiments.

KARI/KICT/KIGAM – South Korea

KICT built a large scale dusty thermal vacuum chamber (DTVC) in 2019. The DTVC is in size of 5 m × 5 m × 5 m (50 m^3 in inner space volume), capable of simulating lunar surface environments such as high vacuum (10^{-4} mbar) and extreme temperature (-190~150℃) with a maximum of 20 metric tons of lunar regolith simulants. To support DTVC operation, a pilot plant is also available for manufacturing 150 kg/day regolith simulants in a given soil physical property. In addition, a smaller DTVC with a volume of 1 m^3 and maximum loading of 300 kg lunar simulants has been successfully used for experimental studies on optimum air evacuation processes with bulky regolith in the DTVC. KICT operates a laboratory of lunar analogue site with a 10 m x 6 m regolith bed with controlled illumination and directional lighting. KIGAM has chambers for metal extraction chambers that can be modified for lunar resources extraction such as oxygen and volatiles and soil processing lines with a simulation program.

LSA – Luxembourg

There are currently no ISRU-specific facilities in Luxembourg. In the short- to mid-term, the European Space Resources Innovation Centre (ESRIC) plans to add equipment depending on the evolution of European research needs in the ISRU domain and the specific requirements of additional public and private strategic partners of the centre, such as a DTVAC.

NASA – USA

In 2016, NASA performed an agency-wide Space Environment Test (SET) facility assessment to examine existing facilities and better align them with on-going and planned ground and flight development activities. The SET facility assessment led to the identification of 1) duplicative facilities with recommendations for facility closure, and 2) gaps in facility capabilities that need to be addressed. After the SET assessment was complete, the NASA ISRU System Capability Leadership Team (SCLT) performed their own assessment of both environmental and operational/analogue test facilities that can accommodate and utilize planetary simulants for regolith/soils during testing. The ISRU SCLT facility assessment led to identifying a significant gap in the ability to test large ISRU systems with regolith under planetary surface conditions, and the directive to utilize existing facilities before initiating construction or work at new facilities that would duplicate test capabilities.

The NASA/US Facilities list is based on an internal assessment of unique NASA facilities that are or plan to be used for on-going and future ISRU technology development efforts. The list also includes external facilities that are known to support on-going NASA-funded ISRU technology development activities or are available to NASA and/or external developers for use. While it is expected that ISRU development activities will constitute the bulk of the testing performed at these facilities, it is anticipated that other surface science and exploration hardware development projects will also utilize these facilities. To achieve a more complete list, a request for information to identify applicable environment simulant facilities with regolith is planned through the Lunar Surface Innovation Consortium, run by the John Hopkins University Applied Physics Laboratory (JHU-APL) under contract to NASA.

UAESA – United Arab Emirates

In 2015, the UAE Space Agency was established to regulate, support, and facilitate the space sector in the UAE. The UAE has set up various government and private facilities that can potentially be used to facilitate ISRU missions.

UKSA – United Kingdom

The UK Space Agency does not possess any internal facilities though there are many facilities throughout the UK that may be capable of supporting ISRU activities. These facilities are operated at University of Industry-level and so are not included in this table. RAL Space (Rutherford-Appleton Laboratory) has a number of national facilities that are available for use, and their website has a detailed account of each of the facilities available, though none are specifically for ISRU purposes.

Table 8. Facilities that Can Accommodate and Use Regolith for Environmental/Operational Testing

Key

(green)	Capability Available
(hatched)	Planned Upgrade
(pink)	Not available - facility dedicated to other user
(grey)	Primarily used by other
White	Capability Not Available

Mars Atm.	- MA1. Mars pressure (6 to 10 torr). Backfilled with CO_2 or Mars gas mix of 95.7% CO_2, 2.7% N_2, 1.6 %Ar - MA2. #1 with active measurement and refill of Mars gases to maintain ratio.
Dust	Represents chambers that can drop or loft dust for abrasion, coating, or filtration testing
Regolith	Represents chambers that can support regolith beds and/or drill tubes
Rock	Represents chambers that can support testing on rocks alone. Note a chambeer that supports Regolith should be able to support Rock testing

Solar	Light spectrum that impacts thermal properties or supports use of solar energy for processing
Radiation	Conveys capability to charge regolith/surfaces (not hard radiation for electronics/etc. like at Brookhaven)

ASI Environment Simulation Chambers

Purpose	Facility Size	Center & Chamber Name	Destination Surface Environment: Dust	Regolith	Rock	Radiation	Solar	Thermal-Low	Thermal - High	Mars Atm.	Vacuum level	Notes	Point of Contact (Name)
Research & Components	200mm x 200mm	PoliMi DAER (Milan) - Dirty Chamber	X	X				100K			10E-3 mbar	Experimental set up to characterize lunar\asteroid simulant physical properties after vacuum and temperature settling before the soil utilisation in relevant analogue physical environment.	Prof. Michèle Lavagna
Subsystem	1,2 m (L) x 1,1 m (D)	Thales Alenia Space Italia (Turin) - Planetary Environment Simulation Chamber (PESCha)	x	x				193 K	413 K	x	5E-6 mbar	TV in representative environment (Moon, Mars) https://webthesis.biblio.polito.it/11257/1/tesi.pdf	Lucia Grizzaffi - lucia.grizzaffi@thalesaleniaspace.com
	3,9 m (L) x 1,0 m (D)	CISAS, University of Padova (Italy) - LISA (Laboratorio Italiano di Simulazione Ambienti)		X	X			80 K		x	2E-3 mbar	Originally established for test of Martian sampling systems, but now also used for Moon applications.	https://www.galletta.it/gg/stampa/lisa/index.html
Subsystem/System	>4 ft (1.2 m) & <14ft (4.25 m)												
Large System	>25 ft (7.62 m)												
Ambient Regolith/Soil Bin Facilities	~40 sqm	Thales Alenia Space Italia (Turin), ROXY (Rovers eXploration facilitY)	X		X						P amb	ROXY is a technological area mainly dedicated to robotic systems design, development and testing, reproducing Mars-like planetary morphology in terms of color, landscape, boulders, smaller rocks and slopes.	Lucia Grizzaffi - lucia.grizzaffi@thalesaleniaspace.com
	19 x 17m	ALTEC (Turin) - Mars and Moon Terrain Demonstrator (MMTD)			X						P amb	Pozzolana Volcanic Tuff (cloddy silty soil) with a depth of 20 cm, filled with gravel and rocks, up to 0.5 m of diameter. The terrain is reconfigurable in terms of crevasses, rock distribution, dunes, hills and ramps. Next development will include a closed structure that will allow a controlled environment and also the simulation of light intensity levels, a "Wind Tunnel" that will allow to reach low temperatures, low pressures and simulate the Martian wind and its effect on the various components of rovers and landers.	Giovanni Martucci giovanni.martucci@altecspace.it
	20x16m Main Arena 8x8m Tilting Platform	ALTEC (Turin)- Mars Terrain Simulator (MTS)	X		X						P amb	Two type of soils: Rheinquartz Phyllosilicates (very fine sand); Pozzolana Volcanic Tuff (cloddy silty soil) with a depth of 20 cm. MTS reconfiguration for Slope generation, Crevasses generators, rocks redistribution. Tilting platform tiltable up to an inclination of 30 deg, with 20 cm depth of soil depth	Giovanni Martucci giovanni.martucci@altecspace.it

CSA/Canada Environment Simulation Chambers (DTVAC)

Purpose	Facility Size	Location & Chamber Name	Dust	Regolith	Rock	Radiation	Solar	Thermal-Low	Thermal - High	Mars Atm.	Vacuum	Comments	PoC
			Destination Surface Environment										
Subsystem >4 ft & <14ft	1000 mm (L) x 1000 mm (D) X 900 mm	CSA DFL (David Florida Labs) - Ottawa, ON, Canada				Charge distribution system	HMI metal-halide spectrum > 800 W/m² (over Ø 0.6 m), > 8000 W/m² (Lamp Focus)	79 K (LN2) 40 K (small platen He)	393 K (LN2)		10 E -05 T	min pressure with 10 kg of dust, without dust 10E-07, also include a platen that can be brought down to 40 K. Dispension system for dust distribution	Elie Choueiry, CSA DFL

DLR Environment Simulation Chambers (DTVAC)

Purpose	Facility Size	Location & Chamber Name	Dust	Regolith	Rock	Radiation	Solar	Thermal-Low	Thermal - High	Mars Atm.	Vacuum	Comments	PoC
			Destination Surface Environment										
Research & Components <4 ft	400mm diameter, irradiation target 80mm diameter	Complex Irradiation Facility, Insitute of Space Systems, DLR Bremen				proton and electron source 1 to 100nA (1 to 10keV); 0.1 to 100 microA (10 to 100keV)	250 to 2500nm (5,000W/m^2), Deuterium UV 112 to 400nm, Argon VUV 40 to 410nm	Liquid nitrogen 80K	target 450C halogen 600W		<10-8 mbar (without VUV-source)	presently, target vertical: adaptation to horizontal possible	Volker Speelmann, DLR: volker.speelmann@dlr.de
											<10-6 mbar (depending on VUV settings)		
Subsystem >4 ft & <14ft	3m diameter	Solar Oven, Institute for Solar Research, Cologne, Germany					22kW at 850W/m^2 direct irradiation with 4.5MW/m^2 flux density				standard and custom vacuum chambers possible	operation possible without vacuum chamber, tested with and without vacuum, site reported for working area, vacuum chambers typically smaller; chamber has been used for volatile extraction	Gerd.Dibowski@dlr.de, https://www.dlr.de/sf/en/desktopdefault.aspx/tabid-10953/
Subsystem >4 ft & <14ft	2m diameter	Solar Simulator, Institute for Solar Research, Cologne, Germany					20kM with 4.2MW/m^2, 10 Xenon-short arc with elliptical reflectors, spectrum similar to solar				standard and custom vacuum chambers possible	operation possible without vacuum chamber, reported size is ambient working area, smaller with vacuum chamber	Gerd.Dibowski@dlr.de, https://www.dlr.de/sf/en/desktopdefault.aspx/tabid-10953/

ESA Environment Simulation Chambers

Purpose	Facility Size	Location & Chamber Name	Destination Surface Environment									Comments	web-site, PoC
			Dust	Regolith	Rock	Radiation	Solar	Thermal-Low	Thermal - High	Mars Atm.	Vacuum		
	500 mm (L) x 400 mm (D)	PECAS, Spanish Astrobiology Center (Spain)					200-500 nm	3 K	325 K		1E-10 mbar	He cooled	https://www.cab.inta-csic.es
Research & Components <4 ft	790 mm (L) x 420 mm (D)	Technical University Munich (Germany)		JSC-1A, JSC-1AF, NU-LHT-2M, NU-LHT-3M, EAC-1, TUBS-M, TUBS-H				77 K	373K on shroud, >1273K locally		1E-6 mbar	Used with Lunar regolith simulant (JSC-1A) for extraction of ice. LN loop embedded in regolith. Gas pressure monitoring. The facility has available and recently used the lunar materials/simulants listed in column E.	https://www.lrg.tum.de/en/lrt/home/ (chair of astronautics), https://www.lrg.tum.de/flr/startseite/ (faculty) contact point:m.rott@tum.de (Dr. Martin Rott, responsible for the facility at the chair), info@lrg.tum.de (faculty info office)
	600 mm (L) x 400 mm (D)	ONERA-DROP (ex ONERA-MARCEL) (France)					VUV (120-160 nm) electron				1E-7 mbar	Used for dust charging experiments, equipped with contactless probe. Used for dust adhesion characterization with centrifugal system.	https://www.onera.fr/en, Jean-Charles.Mateo_Velez@onera.fr
	1200 mm (L) x 1100 mm (D)	PESCha, TAS-I (Italy)						193 K	413 K		5E-6 mbar	min pressure without dust! Leak rate 1.00E-04 mbar*l/s	https://www.thalesgroup.com/en/global/activities/space
Subsystem >4 ft & <14ft	1500 mm (L) x 1000 mm (D)	Open University (United Kingdom)					UV, Xe lamp	80 K			0.5 mbar	chamber to be upgraded soon to lunar environment for PROSPECT ProSPA phase C (probably down to 10E-5 mbar)	http://stem.open.ac.uk/research contact point: Dr Simeon James Barber, simeon.barber@open.ac.uk
	3900 mm (L) x 1000 mm (D)	CISAS, University of Padova (Italy)						80 K			2E-3 mbar	Originally established for test of Martian sampling systems, but now also used for Moon applications. Dry pump and booster with an ultimate vacuum capability of ~10-3 mbar (~2 x 10-3 mbar achieved with full sample container).	https://cisas.unipd.it/il-centro/presentazione
Subsystem/System >14 ft & <25 ft	5000 mm (D)	COMEX hydrosphere (France)		EAC-1			TBD (Feasability study on Xe lamp is currently under investigation)	TBD (Feasability study on LN circulation to create cold volatile zone are being planned for next phase of facility development using exiting liquid circulator networks)	TBD (heat source from Xe lamp and targeted heat zones using ceramic heater are currently evaluatued)		TBD	Currently under ESA contract for conversion of hydrosphere (a hyboberic chamber of 65bar capacity) into a lunar test bed, sphere with 5m diameter. Early tests have achieved 2.8 mbar.	https://comex.fr/en/home/ contact point p.weiss@comex.fr ; m.peer@comex.fr
Large System >25 ft	8000 mm (L) x 2500 mm (D)	Aarhus (Denmark)					solar simulator	153 K	373 K		0.02 mbar	Mars Simulation chamber, wind up to 20m/s, can be considered to adapt for lunar environment.	https://projects.au.dk/marslab/ https://projects.au.dk/marslab/windtunnel-facilities/wind-tunnel/
Ambient Regolith/Soil Bin Facilities	30 m (L) x 15 m (D) x 10 m (H)	ESA LUNA Analog Facility (European Astronaut Centre)		EAC-1			solar simulator					Large scale analog surface simulator for operational aspects, no relevant p, T. To be completed 2021.	Contact Aidan.Cowley@esa.int juergen.schlutz@esa.int

JAXA Environment Simulation Chambers

Purpose	Facility Size	Location & Chamber Name	Destination Surface Environment									Notes	Contact
			Dust	Regolith	Rock	Radiation	Solar	Thermal-Low	Thermal-High	Mars Atm.	Vacuum		
Research & Components	<4 ft (1.2 m)	JAXA Chofu Small chamber									1 x 10^{-5} Pa (vacuum) 1 x 10-3 Pa (dust)	0.2m diamter x 0.1m depth For dust dispersion mechanism	JAXA Wakabayashi wakabayashi.sachiko@jaxa.jp
Subsystem	>4 ft (1.2 m) & <14ft (4.25 m)	JAXA Chofu Medium Chamber									1 x 10^{-5} Pa (vacuum) 1 x 10-3 Pa (dust)	1.5m diamter x3.0m depth For simulated lunar surface	JAXA Hoshino hoshino.takeshi@jaxa.jp
Subsystem/System	>14 ft (4.25) & <25 ft												
Large System	>25 ft (7.62 m)												
Ambient Regolith/Soil Bin Facilities		JAXA Sagamihara Campus Space Explorlation Facility										Area : 23m x 18m, Height: 10m http://www.ihub-tansa.jaxa.jp/afse.html (in Japanese)	JAXA Wakabayashi wakabayashi.sachiko@jaxa.jp

KARI/KIGAM/KICT Environment Chambers

Purpose	Facility Size	Center & Chamber Name	Destination Surface Environment									Notes	Contact
			Dust	Regolith	Rock	Radiation	Solar	Thermal-Low	Thermal - High	Mars Atm.	Vacuum		
Research & Components	<4 ft (1.2 m)	KIGAM_Pyro						300 °C	1800 °C		1 x 10^{-4} ~ 0.01 torr / open	Purpose: high temperature electrolysis and high temperature metallurgical processing Auxiliary equipments: gas/dust analyzer, potentiostat, power supply, glove box, cold trap	Kyeong Kim (kjkim@kigam.re.kr) /Jungshin Kang (jskang@kigam.re.kr)
		KIGAM Heavy Ion Implanter				<500 keV ion 1E+18 ion/cm2/s	Terminal V: 10-500kV	Ambient	400°C		1 x 10^{-6} torr	Ions (H+, H2+, He+, C+, N+, O+, Ar+, Kr+, Xe+), X-ray level <5µSv/hr, chamber size: 50cm (ϕ) x 25cm (L), traget size: 1~4 inch Characterization of space materials and electronics parts, ion implantation	Kyeong Kim (kjkim@kigam.re.kr)
		KIER 35 kWt solar furnace						Ambient	1,500K			9.8 m dia. parabolic dish type concentrator and 10 m x 10 m heliostat	Kyeong Kim (kjkim@kigam.re.kr) /Jong-kyu Kim (rnokim@kier.re.kr)
Subsystem	>4 ft (1.2 m) & <14ft (4.25 m)	KICT Small DTVC (Dusty Thermal Vacuum Chamber)	Electrostatically changing	Max. 300 kg with a soil bin in DTVC				-196°C/77K (	+150 C		$1x10^{-8}$ torr ($1x10^{-4}$ torr with simulant)	Chamber internal dimension (Φ 1m x L 1m) KLS-1 lunar regolith simulant in a test bin consisting of a W 0.7m x L 1.0m x H 0.3m	Hyu Soung Shin in KICT; e-mail: hyushin@kict.re.kr
Subsystem/Sys	>14 ft & <25 ft (7.62 m)	KICT Large DTVC (Dusty Thermal Vacuum Chamber)	Electrostatically changing	Max. 20 metric tons with a soil bin in DTVC				-196°C/77K (	+150 C		$1x10^{-8}$ torr ($1x10^{-4}$ torr with simulant)	Chamber internal dimension (W 4m x L 4m x H 4m) KLS-1 lunar regolith simulant in a test bin consisting of a W 3.7m x L 3.9m x H 1.4m	Hyu Soung Shin in KICT; e-mail: hyushin@kict.re.kr
Large System	>25 ft (7.62 m)												
Ambient Regolith/Soil Bin Facilities		KIGAM-comminution & monitioring system						-10°C	40°C		open	Commiuntion machines for grinding and mixing reources - Jaw, cone and hammer crusher, ball and disc mill - Simulation tool for cominution : Discrete simulation software (EDEM/ DEM solutions) Cominution monitoring system : vibration & acustic sensing sysytem - Chamber volume : 30cm(Φ) x 20cm(H) - Measured frequency range: 0.2hz - 10khz - Maximum measurement acceleration: 5,000m/s2	Kyeong Kim (kjkim@kigam.re.kr) /Kwangsuk Yoo (youks@kigam.re.kr) /Hoon Lee (hoonlee@kigam.re.kr)

NASA/US Environment Simulation Chambers

Purpose	Facility Size	Location & Chamber Name	Dust	Regolith	Rock	Radiation	Solar	Thermal-Low	Thermal-High	Mars Atm.	Vacuum	Notes	Contact
			Destination Surface Environment										
Research & Components <4 ft (1.2 m)	0.78 m dia. x 1.2 m. long. (31in x 48in)	MSFC LETS				50 & <2 KeV electron guns, ion gun	UV & Quartz lamp	-196°C/77K (	71°C/344 K		1 x 10^{-7} torr	Part of Space Environmental Effects (SEE) facility. The chamber is configurable with multiple ports so the equipment on it varies.	Paul Craven, PhD, paul.craven@nasa.gov Mary Nehls, mary.nehls@nasa.gov
		MSFC HISET											
	24"dia. x 32" tall	JSC 361 Bell Jar						-50°C/223 K	-200°C/437 K		2 x 10^{-7} torr	Belljar chamber with internal shroud connected to a Julabo Presto A80 temperature control system. LN2 compatible.	Mike Reddington Email: Michael.Reddington-1@nasa.gov
		JPL 183 MOXIE						-196°C/77K (	71°C/344 K	MA2	1 x 10^{-7} torr	Thermal box can raise temps up to 1400 C	Jim Lewis & David Vaughan Email: james.r.lewis@jpl.nasa.gov
	30"×30"×48"	KSC IVI ESPL filtration						Ambient		MA2	1 x 10^{-7} torr	Part of Electrostatic and Surface Physics Laboratory (ESPL) which is located within KSC's Swamp works facility. The chamber is configurable with multiple ports so the equipment on it varies.	Carlos Calle Email: carlos.i.calle@nasa.gov
	24 in tall, 18 in dia.	GRC 77 MACS	??					-50°C/223 K	Ambient	MA2	5 to 10 torr	Cold wall (24 in without)	
		GRC 77 Particle Flow Loop Filtration						Ambient		MA1	. torr to ambien	Particle Flow Loop (Dust filtration); Axial flow rates up to 100 cfm. Standard size particle generation: mono-size silica spheres (0.25nm to 3 µm)	Juan Agui Email: juan.h.agui@nasa.gov
	2' dia. x 2' long	GRC Mech. Chamber	??		??			-196°C/77K (LN_2) to hardware	Ambient	MA1	1 x 10^{-7} torr	vacuum chamber with LN2 feedthrough to hardware. Pressure can also be controlled to Mars ambient with appropriate Mars atmosphere mixed gas. Focus on mechanism exposure and durability testing	Adam Howard: howard@nasa.gov
	30" Belljar	LaRC Cryo Bell Jar						Cryo Helium	Ambient		1 x 10^{-5} torr	30" Belljar chamber with helium cooled shroud and conductive platen. Temperatures between 40K and 373K.	Mark N. Thornblom Email: mark.n.Thornblom@nasa.gov
	1 m x 1 m x 1 m	Honeybee Robotics Medium TVAC Chamber						-70 C	Ambient		1 mtorr		Kris Zacny E-mail: KAZacny@honeybeerobotics.com
	1.06 m dia. x 1.37 m. long. (42in x 54in)	Colorado School of Mines - OMTC						-196°C/77K (	+150 C		1 x 10^{-7} torr	32 KWe Lamp	Chris Dreyer, cdreyer@mines.edu
Subsystem >4 ft (1.2 m) & <14ft (4.25 m)		GRC VF13						-196°C/77K (LN	71°C/344 K	MA2	1 x 10^{-6} torr	Internal dimensions: 3.6 m tall, 1.35 m diameter with cold wall (1.5 m without)	Julie Kleinhenz Email: Julie.e.kleinhenz@nasa.gov
		Honeybee Robotics Large TVAC Chamber						-196°C/77K (	+100 C		1x10^{-3} torr	3.5 m x 1 m x 1 m.	Kris Zacny E-mail: KAZacny @honeybeerobotics.com
		Michigan Tech PSTDL DTVAC						-196°C/77K (LN	+200 C		1x10^{-6} torr (1x10^{-4} torr with simulant)	1.27 m wide, 1.34m tall, 1.77m long inside thermal shroud (1.21 m x 0.6 m x 1.72 m in regolith bin)	Paul van Susante Email: pjvansus@mtu.edu
		NREL High-Flux Solar Furnace					Conc. sunlight					Concentrate solar radiation to 10 kilowatts over a 10-cm diameter (2,500 "suns"), achieving temperatures of	https://www.nrel.gov/csp/facility-hfsf.html
		White Sands Missile Range Solar Furnace					Conc. sunlight						
Subsystem/ System >14 ft (4.25) & <25 ft (7.62 m)	10' dia, 37' tall	JPL #73						-196°C/77K (	71°C/344 K	MA1	1 x 10^{-5} torr	Full access. Currently in use for Mars 2020 sample collection	
	15' Spherical	JSC B351						-196°C/77K (	148°C/421 K		1 x 10^{-6} torr	15' Φ Spherical Chamber with ~78" Φ clear entry. Initial operations planned for end of CY20	Mike Reddington Email: Michael.reddington-1@nasa.gov
	20' Spherical with 78" "Ears"	JSC B353						-196°C/77K (LN	Ambient	MA2	5 to 10 torr	20' Spherical Chamber with 78" "Ears", 10' door, and 17' floor. Vaccum capability upgrade under consideration	Mike Reddington Email: Michael.reddington-1@nasa.gov
	12' dia x 15' Vertical	MSFC Stand 300 - 12 ' Vac							Ambient		1 x 10^{-3} torr	1700 ft 3 , 12' diameter x 15' Vertical Chamber. Aimed at thrust/regolith interactions and thermal protection systems	

Large System >25 ft (7.62 m)		LaRC 16 m Chamber						-196°C/77K (LN_2) Cold Plate	Ambient	Air at Mars Pressure	150×10^{-3} torr	Used or high altitude aeronautics testing, the facility	
	65' Dia by 120' Tall	JSC Chamber A (#119)						-253°C/20K (LN_2/He)	Ambient	MA1	1×10^{-6} torr	Cylindrical Chamber with 40' Main Access door	Mike Montz Email: michael.e.montz@nasa.gov
	15' dia x 25' Vertical	MSFC Stand 300 - 15 ' Vac							Ambient		1×10^{-3} torr	4500 ft 3 , 15' diameter x 25' Vertical Chamber. Aimed at thrust/regolith interactions and thermal protection systems	Jim Sisco; jimmy.d.sisco@nasa.gov
Ambient Regolith/Soil Bin Facilities	25' x 25' x 3' deep	KSC Large Regolith Test Bed										25' x 25' x 3' deep enclosed soil bin containing BP-1 basalt	Drew Smith Email: jonathan.d.smith@nasa.gov
	6' x 6' x 1' deep	KSC Small Enclosed Soil Bin										6' x 6' x 1' deep enclosed soil bin containing 2 metric tons of JSC-1A basalt lunar regolith simulant	Drew Smith Email: jonathan.d.smith@nasa.gov
	2m x 3m x 0.3m	GRC SLOPE Facility										Large soil tank (12m x 3m x 0.3m) containing GRC-1 lunar simulant ; Adjustable tilting soil tank (6m x 5m x 0.3m, 0 to 45 deg) for sloped surface operations; Sink Tank (12m x 3m x 0.6m) containing a high-sinkage soil (Filliti) used to simulate vehicle entrapment conditions on Mars	Erin Rezich E-mail: erin.t.rezich@nasa.gov
	two adjacent (each 3m x 2m x 0.75m)	GRC – Traction and Excavation Capabilities (TREC) Rig										TREC rig features a heavy-duty carriage capable of driving across two adjacent soil bins (each 3m x 2m x 0.75m) for evaluation of excavation tools and wheels; Single-wheel tester can handle tires up to 90 cm diameter & 45 cm width	Erin Rezich E-mail: erin.t.rezich@nasa.gov
	1.8m x 0.75m x 0.75m	GRC – Excavation Laboratory										Heavy-duty robotic arm capable of excavating from multiple adjacent soil bins (1.8m x 0.75m x 0.75m) for evaluation of excavation tools and forces 2m x 1m vibrating table for compacting simulant to maximum densit	Phillip Abel E-mail: phillip.abel@nasa.gov
	4 m x 4 m x 0.5 m	ARC - SSERVI Soil Bin										JSC-1A lunar regolith simulant in a test bin consisting of a 4 m x 4 m x 0.5 m	Greg Schmidt
		NASA Facility 'Rock Yards'										Outdoor rockyards exist at ARC, GRC, JPL, JSC, and MSFC for mobility platform testing. An outdoor facility exists at KSC for mobility and lander testing	

UAE Environment Simulation Chambers (DTVAC)

Purpose	Facility Size	Location & Chamber Name	Destination Surface Environment										
			Dust	Regolith	Rock	Radiation	Solar	Thermal-Low	Thermal - High	Mars Atm.	Vacuum	Comments	PoC
Research & Components <4 ft	0.35 m Length: 0.4 m	KUSTIC - Khalifa university Diameter:						-50°C/ 77K (	200°C/473 K		1×10^{-6} torr		
	0.8 m length: 0.6 m	NSSTC (UAE U) TVAC Chamber Diameter:						-60°C/ 333.15K (Silicone oil based TCUs)	120°C/ 393.15 K		5×10^{-6} torr	ready by Q2 2021	
Subsystem >4 ft & <14ft	2 m length: 2 m	NSSTC (UAE U) TVAC Chamber Diameter:						-60°C/ 333.15K (LN2)	120°C/ 393.15 K		1 x 10-6 torr	ready by Q4 2021	

REGOLITH SIMULANT ASSESSMENT

The purpose of the Regolith Simulant Assessment is to provide information on regolith simulants that are expected to be useful in the testing and development of various equipment to be operated in the lunar and/or Martian environment. For instance, the development of material processing plants, vehicles roving around, and construction machines will definitely require terrestrial function tests using simulants on the surface environment.

A crucial component of a high-fidelity planetary simulation is a regolith simulant that simulates a comprehensive set of properties. For example, lunar simulants have evolved from generic basaltic dust used early in the Apollo Program to simulants that more closely mimic the bulk chemistry of the returned lunar samples. There has also been an increasing emphasis on volcanic glass content and better control over the size and shape distribution of simulant particles. But it is increasingly recognized that minor constituents will in some cases have major impacts. Small amounts of sulphur in the regolith can poison catalysts, and metallic iron on the surface of nano-sized dust particles may cause a dramatic increase in its toxicity.

A further challenge is the fact that the definition of a high-fidelity simulant is application-dependent. For example, in-situ resource utilization will require high fidelity in chemistry, meaning careful attention must be paid to minor components and phases; but some other applications, such as those concerned with abrasive effects on suit fabrics, might be relatively insensitive to minor component chemistry while abrasion of some metal components may be highly dependent on trace components. In some cases, these minor constituents will introduce complications, but in others, the minor constituents may prove to be beneficial.

There is also a growing awareness that the surface of the regolith particles may well be altered by solar and cosmic radiation, and the changes in surface chemistry may have implications for such surface-dependent properties as adhesion and biological activity. Research must be conducted to determine how sensitive the various mitigation and utilization technologies will be to minor components and environmental factors before those factors can be dismissed as unimportant.

<u>ASA/CSIRO – Australia</u>

Australia does not currently produce simulants for ISRU related activities but has used a range of internationally-available simulants in ISRU research to date.

<u>ASI – Italy</u>

At the moment, ASI and other involved National Research entities benefit from ISRU simulants facilities of other countries.

<u>CNES – France</u>

CNES does not produce its own simulant for ISRU tests. When needed for its own tests, CNES (as ESA Member State) asks ESA/EAC to have a bit of the EAC-1lunar regolith simulant.

<u>CSA/NRCan – Canada</u>

A number of simulants listed in the table have been developed and utilized over the years. At this point, none of these have been maintained due to the availability and demand. Recently, the OB1A is being considered as a replacement for the previous simulant. Its characteristics are provided in the Table. Depending on the demand, production of the simulant is envisaged by the CSA and Canadian industry.

<u>DLR – Germany</u>

ESA-EAC-1 as well as several TUBS simulants have been produced in Germany in Cologne and Braunschweig, respectively. They add to the variety of other simulants that are in use for certain aspects of specific projects. These efforts contribute to the overall supply of simulants and also benefit from partners.

ESA – Europe

ESA has been identifying and utilising simulant material for a variety of engineering applications in the past and has actively developed (and is planning further developments) of simulant material. For example, the EAC-1 material, a large volume regolith simulant for LUNA, has been sourced for this facility in significant quantities. Additional work on bespoke simulants for scientific and specific engineering purposes has also been undertaken under the guidance of the Sample Analogue Curation Facility at the ESA ECSAT centre, where a range of simulants are maintained and distributed for research involving simulants.

JAXA – Japan

The listed table shows lunar regolith simulants produced in Japan for lunar mare, highland, and soil. As overseers' simulants cannot easily be imported and used in large quantities because of transportation cost and period as well as quality control during transportation. The simulants are made available in Japan to be delivered at any time and place in Japan immediately upon request.

KARI/KICT/KIGAM – South Korea

KIGAM has developed a highland lunar simulant, KIGAM-L1, and will continuously develop few more lunar simulants for the purpose of its prospective research project on lunar resource extraction.
KICT already developed KLS-1 in 2015 which has similar physical and mechanical properties with JSC-1 and FJS-1. They have been used for environmental verification tests in DTVC and raw materials for making lunar construction blocks.

LSA – Luxembourg

No work on simulants is currently being performed in Luxembourg.

NASA – USA

With the cancellation of NASA's human lunar exploration Constellation program in 2010, production of lunar simulants stopped and stockpiles of the material have dwindled over time. As plans for the new Artemis robotic and human lunar exploration program in the US have advanced, it became readily apparent that large amounts of new lunar regolith and dust simulants will be needed to support technology and system development of ISRU and other lunar surface hardware. In 2020, NASA initiated a new Simulant project with the aim of 1) assessing the requirements/needs for simulants, 2) assessing current stockpiles and producers of simulants, 3) assessing the type and quality of past/current simulants, 4) provide advice/guidance on the 'best' type of simulant to use for development of specific technologies and hardware, and 5) recommend production of new simulants and terrestrial feedstock for identified gaps. The NASA/US list is a 'snapshot' of the past/existing simulants available to NASA and NASA-funded researchers and developers. At this time, it has not been determined if all new simulants will be procured commercially, or if NASA will help or lead production of new simulants for simulant gaps still to be identified.

UAESA – United Arab Emirates

With the start of Emirates Mars Mission in 2015, the UAE established Mars 2117 Strategy that leads the vision to establish a Habitant on the Martian Surface. This initiative led to several Programs that could support ISRU projects such as the UAE Astronauts Program which is building the capabilities to lead Manned Missions that could use the ISS to facilitate ISRU mission.

UKSA – United Kingdom

The UK Space Agency does not produce its own simulants for ISRU experiments. A number of UK universities and research organisations produce their own simulants for internal use. The UK is also home to ESA ECSAT facility that houses the Sample Analogue Curation Facility.

Table 9. Simulants

	Lunar Regolith Simulants	Info	Type	Contact Info/Comments	Supply Confidence
Canada	OB-1	Shawmere anorthsite and olivine glass slag; Battler (2009)	Average highlands (general)	Dale Boucher, dboucher@deltion.ca	
	Chenobi	Shawmere anorthsite and Shawmere-derived glass and agglutinates; Weinstein (2008)	Average highlands (general)	Dale Boucher, dboucher@deltion.ca	
	OB-1A	Shawmere anorthsite and olivine glass slag	Average highlands (general)	Dale Boucher, dboucher@deltion.ca	TBD
	UW-1M	Lunar mare with nanophase Fe	Lunar mare	CSA / Univ. Winnipeg	TBD
	UW-1H	Lunar highland with nanophase Fe	Lunar highlands	CSA / Univ. Winnipeg	TBD
ESA	Lunar Regolith Simulants	Info	Type	Contact Info/Comments	Supply Confidence
	DNA-1	Bolsena Lake (Italy)	Low Ti Mare	Laurent Pambaguian/ESA	
	EAC-1a	European Astronaut Centre mare simulant (Engelschion et al, 2020)	Low Ti Mare (geotechnical), large volume	Aidan Cowley, Dayl Martin/ESA, large volume simulant for LUNA facility	
	TUBS-T	Anorthosite base, Technical University Braunschweig (Linke et al, 2019)	Highlands (general)	Stefan Linke, TUB	
	TUBS-H	Basalt base, Technical University Braunschweig (Linke et al, 2019)	Low Ti Mare (general)	Stefan Linke, TUB	
	UoM-Black	University of Manchester (Just et al, in review)	large volume, mechanical	Gunter Just, UoM	
	UoM-White	University of Manchester (Just et al, in review)	large volume, mechanical	Gunter Just, UoM	
	AGK-2010	Polish Lunar Simulant/AGH University of Technology	Geotehnical	Karol Seweryn, Polish Academy of Sciences	
	Mars				
	ES-1	Engineering Soil 1 - ESA TN-MMA-MVW-20140606	Fine dust (Nepheline Syenite) from Sibelco, Norway. Large volume, mechanical.	Unknown availability. May be obtained from RUAG.	
	ES-2	Engineering Soil 2 - ESA TN-MMA-MVW-20140606	Silverbond D6 DD fine quartz sand (from Sibelco, Belgium).	No longer available from manufacturer. May be obtained from RUAG.	
	ES-3	Engineering Soil 3 - ESA TN-MMA-MVW-20140606	OMR Dry (from Sibelco Ltd. UK). Mixture of coarse and medium components.	No longer available from manufacturer. May be obtained from RUAG.	
	ES-4	Engineering Soil 4 - ESA TN-MMA-MVW-20140606	Mixture of ES-1 and ES-3.	May be available from RUAG.	
	OUCM-1 and CM-2	Open University	Contemporary Martian Simulants	Open University	
	OUEB-1 and EB-2	Open University	Early basaltic	Open University	
	OUHR-1 and HR-2	Open University	Haematite rich	Open University	
	OUSR-1 and SR-2	Open University	Sulfur rich	Open University	
Japan	Lunar Regolith Simulants	Info	Type	Contact Info/Comments	Supply Confidence
	FJS-1	Crushed basaltic lava from Mt. Fuji area	Average luna mare (general)	uyama@shimz.co.jp	
	FJS-1g	Crushed basaltic lava from Mt. Fuji area, scoria	Average luna mare (general), enhanced glass		
	Oshima Base Simulant	Crushed basalt from Izu-Oshima island, Olivine, ilmenite	Average luna mare		
	Kohyama Base Simulant	Crushed Gabbro from Kohyama (Japan) area	Average luna highland (general)		
	FJS-2	Crushed basaltic lava from Mt. Fuji area, olivine	Average luna soil (general: Apollo14 site)		
	FJS-3	Crushed basaltic lava from Mt. Fuji area, olivine, ilmenite	Luna mare (High Titanium model)		
Korea	Lunar Regolith Simulants	Info	Type	Contact Info/Comments	Supply Confidence
	KLS-1	Korea Lunar Stimulant(Ryu et al, 2018)	large volume, mechanical	Korea Institute of Civil Engineering and Building Technology, KICT	
	KIGAM-L1	Korea Institute of Geoscience and Mineral Resources	highland (general), small volume	Korea Institute of Geoscience and Minearl Resoureces, KIGAM	
United States	Lunar Regolith Simulants	Info	Type	Contact Info/Comments	Supply Confidence
	OPRH2N	https://www.offplanetresearch.com/simulants-feedstocks-and-addatives	Average highlands, Apollo based (general)- 70% anorthosite, 30% basaltic cinder	Melissa Roth, melissa@offplanetresearch.com	
	OPRH3N	https://www.offplanetresearch.com/simulants-feedstocks-and-addatives	Average highlands, Apollo based (general)- 80% anorthosite, 20% basaltic cinder	Melissa Roth, melissa@offplanetresearch.com	
	OPRL2N	https://www.offplanetresearch.com/simulants-feedstocks-and-addatives	Average mare, Apollo based (general)- 90% basaltic cinder, 10% anorthosite	Melissa Roth, melissa@offplanetresearch.com	
	OPRL2NT	https://www.offplanetresearch.com/simulants-feedstocks-and-addatives	h-Ti mare, Apollo based (general)- 77% basaltic cinder, 8.6% anorthosite, 14.4% ilmer	Melissa Roth, melissa@offplanetresearch.com	
	OPR Agglutinate	https://www.offplanetresearch.com/simulants-feedstocks-and-addatives	Agglutinate component made out of any of the above simulants	Melissa Roth, melissa@offplanetresearch.com	
	LHS-1	https://sciences.ucf.edu/class/simulant_lunarhighlands/	Average highlands, Apollo 16 based (general)	Mike Conroy, mike.conroy@ucf.edu	
	LMS-1	https://sciences.ucf.edu/class/simulant_lunarmare/	Average mare, moderate Ti (general)	Mike Conroy, mike.conroy@ucf.edu	
	NU-LHT series	Stillwater Complex, MT rocks + minerals; Stoesser et al. (2010) NASA/TM-	Average highlands, Apollo 16 based (general)	John Gruener, john.e.gruener@nasa.gov	
	JSC-1	Basaltic volcanic ash; McKay et al. (1994) Space 94;	Average mare (general)	John Gruener, john.e.gruener@nasa.gov	
	JSC-1A series	Basaltic volcanic ash; Ray et al. (2010);	Average mare (general)	John Gruener, john.e.gruener@nasa.gov	
	JSC-1 and JSC-1A feedstock	Basaltic volcanic ash; Merriam Crater, Flagstaff, AZ;	Average mare (general)	John Gruener, john.e.gruener@nasa.gov	
	BP-1	Black Point lava flow, AZ	Average mare (general)	Laurent Sibille, laurent.sibille-1@nasa.gov	
	MLS-1	Basalt from Duluth, Minn.; Weiblen et al. (1990) Space 90	High-Ti mare, Apollo 11 based	John Gruener, john.e.gruener@nasa.gov	
	GreenSpar	Greenland Anorthosite; Gruener et al. (2020) LPSC;	Average highland anorthosite, An 78-86 (general)	John Gruener, john.e.gruener@nasa.gov	
	GRC-1 and GRC-3	Manufactured sand; GRC-1, Oravec et al. (2010); GRC-3, He et al. (2013)	Terramechanics testing	Colin Creager, colin.m.creager@nasa.gov	
	Mars				
	MGS-1	https://sciences.ucf.edu/class/simulant_marsglobal/	Global basaltic soil based on the mineralogy of the Rocknest target at Gale crater	Mike Conroy, mike.conroy@ucf.edu	
	MGS-1S	https://sciences.ucf.edu/class/simulant_mgs1s/	MGS-1 simulant enhanced with gypsum	Mike Conroy, mike.conroy@ucf.edu	
	MGS-1C	https://sciences.ucf.edu/class/simulant_mgs1c/	MGS-1 simulant enhanced with smectite	Mike Conroy, mike.conroy@ucf.edu	
	JEZ-1	https://sciences.ucf.edu/class/simulant_jez1/	MGS-1 simulant enhanced with smectite, Mg-carbonate, and olivine	Mike Conroy, mike.conroy@ucf.edu	
	JSC Mars-1	Weathered basaltic ash Pu'u Nene, Hawaii; NASA JSC; Allen et al. (1998)	Average bright soil	John Gruener, john.e.gruener@nasa.gov	
	JSC Mars-1A	Weathered basaltic ash Pu'u Nene, Hawaii; Orbitec	Average brigh soil	John Gruener, john.e.gruener@nasa.gov	
	JSC-RN	MMS base + water- and volatile-bearing minerals; Clark et al (2020);	Rocknest aeolian sand shadow, for water extraction	Joanna Clark, joanna.hogancamp@nasa.gov	
	MMS	Saddleback basalt, Mojave Desert, CA; Peters et al. (2008);	Average weathered Mars basaltic soil	Greg Peters, gregory.h.peters@nasa.gov	

Key

- = Currently available
- = Previously produced, some stockpiles exist, can be reproduced if needed
- = Previously produced, some stockpiles exist, may be difficult to reproduce if needed
- = Previously produced, no/limited stockpiles exist

GAP ASSESSMENT

The Gap Assessment of all knowledge and technologies useful for ISRU applications to make possible sustainable human long-duration presence on the Moon (and in the future on Mars) is here presented. The purpose of this section of the report is not to provide a detailed assessment of the technologies identified in Appendix B "Technology Capture by WBS and Country/Space Agency", but to provide a general understanding of the current work and potential gaps derived from examining the table. Readers are encouraged to examine Appendix B closely (even though it may not be complete).

The sustainability of human long-duration presence poses considerable challenges in the development and demonstration of technologies finalized to the ISRU goals: it implies the development of innovative technologies as the appropriate adaptation of some technologies already available. The spread among the current and the desirable status of the interesting technologies is strongly linked to the costs in implementation time and costs investments necessary to obtain the appropriate maturity levels.

GAP ASSESSMENT METHODOLOGY

Starting with the systematic mapping of each knowledge, technology, and process useful for the ISRU aims, the Working Group members identified the gaps by assessing the issues/needs and requirements for key technical challenge areas against the status at each agency. In the assessment criteria, it was also taken into account the State of Art in the Terrestrial Context and the development level needed for Spin-in. This mapping activity was conducted for the following 6 Functional Breakdown areas and associated sub-areas, as extrapolated from Appendix B. "Technology Capture by WBS and Country/Space Agency":

1. **Destination, Reconnaissance, and Resource Assessment**
    - Site Imaging/terrain mapping;
    - Resources assessment (for physical/geotechnical, mineral/chemical, subsurface ice, and water/volatile characterization);
    - Orbital site and resources evaluation (surface imaging and mineralogy, imaging in PSR, higher resolution water/ neutron spectroscopy);
    - Local surface resource evaluation (integrated instruments for processing and site selection, mobility-traversability for resource assessment, autonomy for resource assessment, communication & navigation for resource assessment);
    - Resource/terrain/environment data fusion and analyses.

2. **Resource Acquisition, Isolation, and Preparation**
    - Gas resource collection, separation, and preparation (Mars CO_2 and AR/N_2);
    - Solid resource excavation/acquisition (granular, hard mineral, and/or icy);
    - Resource preparation before processing (size reduction, crushing/grinding, mineral separation, size sorting, fractions);
    - Resource transfer (granular material and gas transfer);
    - Resource delivery from mine site and removal (mobility-traversability for resource delivery/removal, autonomy for resource delivery/removal, communication & navigation for resource delivery/removal).

3. **Resource Processing for Production of Mission Consumables**
    - Regolith processing to extract oxygen (physical/chemical);
    - Regolith Processing to Extract Water (surface-fed reactor, Subsurface enclosed reactor, Remote subsurface heating/vapor collection);
    - Carbon Dioxide (CO_2) Processing (CO_2 to oxygen, to methane and water, to hydrocarbon, to carbon, and to high-value compounds);

- Water processing (electrolysis, capture/storage);
- Instrumentation to characterize processing performance (instruments for mineral and for product purity characterization);
- Product/reactant separation & recirculation (chemical, passive, thermal separation);
- Contaminant removal from reagents/products (water and gas clean-up).

4. **Resource Processing for Production of Manufacturing and Construction Feedstock**
    - Regolith manipulation for manufacturing/construction feedstock;
    - Resource processing to extract metals/silicone;
    - Resource processing to produce plastics/binders;
    - Autonomous/supervised processing operations.

5. **Civil Engineering and Surface Construction**
    - Site planning and design
    - Site preparation (terrain shaping, area clearing/levelling/grading, surface stabilization, below-grade operations, and support, berm construction);
    - Construction material preparation (size/shape manipulation, component mixing, conveyance, clean/quality control);
    - Construction processes and support (additive construction, brickmaking/press, direct sintering/melting, supports/structure/framework, joining, post-construction lining);
    - Horizontal construction (road, foundation, landing/launch pad construction);
    - Vertical construction & shielding (underground, above-ground unpressurized structures & shielding, above-ground pressurized structures).

6. **In-Space Manufacturing**
    - Manufacturing material preparation (wire/filament, polymers, regolith);
    - Manufacturing processes and support (additive, subtractive and composite manufacturing, near net shape);
    - Part finishing/verification (CNC milling, heat treatment);
    - Part joining (welding);
    - Assembly (welding);
    - Manufacturing waste recycling (polymer, metals);
    - Maintenance & life cycle (in-process monitoring, inspection, and compliance, decommissioning /salvage).

Destination, Reconnaissance, and Resource Assessment

Regarding the resources assessment, it will be particularly critical to obtain more information to understand 1) conditions as a function of depth, 2) conditions at the lunar poles inside and outside of PSRs, and 3) hardness of resources if crushing/grinding is required. Moreover, instruments need to be refocused for 1) lunar operation, 2) minerals of resource interest, 3) faster operation for wide-area and localized resource assessment and to find and map subsurface ice deposits. A depth profile of volatile release as well as profiles across a broad area are required to finalize mining techniques. Advances are being made in all of these areas, and several missions to begin surface assessment of polar ice and resources are in development. In particular, the NASA RESOLVE and the ESA PROSPECT instrument package development efforts are aimed at providing the ability to better understand the depth profile of water and volatiles.

As for the orbital site resources evaluation, detailed maps of minerals on the lunar surface and detailed understanding of surface topography and terrain features are required. Neutron spectrometers with Lower altitudes and time over target are needed to refine maps of possible water locations on the Moon. Higher resolution imagery and surface topography understanding within PSRs is also required to better plan resource assessment and mining operations as well as potential support direct landing within PSRs. Missions associated with further orbital understanding of polar resources to help close the gaps in knowledge are in development, such as the LunaHMap, IceCube, and Lunar Flashlight CubeSats, Lunar Trailblazer orbiter, Korea Pathfinder Lunar Orbiter with NASA ShadowCam instrument, and Luna 26 orbiter.

As for the local surface resources evaluation, more types of data, more samples of data, and a wider range of locations and areas covered are needed to properly assess the resource potential and analyse the site before final mining operations can begin. Mobile assets will be required to traverse successfully across a potentially wide range of surface material properties. Resource mapping in a PSR requires navigation in sunlight denied locations with the need for geo-tagging/localization of information/data collected for resource data fusion and future mining operation planning. The NASA VIPER mission will perform the first surface assessment of regolith physical and mineral properties and water content near and in permanently shadowed regions. The mission is expected to last several months and traverse tens of kilometres. The mission will assess water content that may exist on the surface with an infrared spectrometer, and subsurface water via a neutron spectrometer (measures hydrogen down to ~1 meter), a 1-meter auger that brings subsurface material to the surface, an infrared spectrometer that will analyse subsurface material and a mass spectrometer which will measure water and other volatiles released during transfer. While this mission will provide critical information that is currently lacking for resource understanding and mine equipment design and development, much more information is required on the scope, distribution, and content of water and other volatiles in lunar PSRs. In particular, information from surface and subsurface sample heating to drive off water and volatiles as a function of temperature, as well as more measurements for physical and mineral characteristics of PSR regolith. While stationary, Luna-27 mission with the ESA PROSPECT instrument will begin to provide some of the in-situ measurements that the VIPER mission will not provide.

All the data collected from various instruments need to be integrated and models to predict/select the most likely locations for missions need to be accordingly refined.

Resource Acquisition, Isolation, and Preparation

Solid material excavation and acquisition can be performed on Moon and Mars to extract the needed resources. For collection/excavation of granular raw materials, long-duration operation instrumentations must be suitable for granular abrasive materials to avoid their wear. Smaller and longer-duration operations vehicles can minimize excavation energy needs. For hard raw materials, it needs to consider longer-life motors, lubrications, and appropriate mechanical operations to perform correctly excavation. The effects of ice sublimation after excavation and up to processing must be minimized.

The solid raw materials need to be prepared before the processing phase: size reduction and crushing/grinding need very power-intensive and high endurance devices. Terrestrial instrumental units are very heavy and need to be adapted to avoid all the problems this implies on Moon and Mars, like transportation and management. Wear resistance or ease of replacement will also be needed if crushing/grinding is required.
To increase performance and reduce energy, desired minerals need to be separated and selected through appropriate methodology, which could be strongly dependent on the mixing of minerals in the rocks and regolith. Multiple separation passes could be required with the support of real-time assessment devices to measure separation performance. The size sorting/fractions method requires some units of the devices for materials/screen/rotating selection: these devices can be worn-out by the abrasive effect of jagged and irregular shapes of regolith, or damaged by potential electrostatic issues.

Removal and delivery of raw resources from mine site need integrated methods to implement mobility operations, taking also into account wear on materials and mechanisms, especially wheels and locomotion systems. Transfer of tons of granular materials as regolith or ground rocks per year can lead to bridging, clogging in rotating surfaces devices, and gas losses/recycling for pneumatic transfer. The surface soil will most likely also degrade due to repeated traverses over the same location. Appropriate solutions to maintain traversability must be considered. This may include examination of wheel designs as well as the establishment of 'roads' between the excavation site and processing unit. A significant amount of work has been performed on granular material excavation devices and mobile excavators that have been tested under terrestrial conditions. However, only a limited amount of work has been performed under lunar vacuum and temperature conditions.

In Mars's case, for the gas resource collection, separation, and preparation, it can be done for some chemical species directly from its atmosphere. Carbon dioxide (CO_2) is used for molecular oxygen (O_2) and methane (CH_4) productions, efficient chemical processing requires pressures of at least 8 psi to 45 psi, a pressure increase of 2 orders of magnitude above the ambient ~0.1 psi pressure. A selective system of gas collection procedure is essential to remove other gases to avoid the contamination of final products or their build-up in regenerative chemical processing systems. The gas acquisition systems must operate continuously for extremely long durations and in presence of dust. Advances have been made in technologies for the acquisition and compression of the Mars atmosphere for subsequent processing. The scroll compressor on the Mars Oxygen ISRU Experiment (MOXIE) on the Mars 2020 Perseverance rover will advance the capability by actually demonstrating atmospheric compression on Mars. In parallel, a larger scale unit is also under development.
Nitrogen (N_2) gas needs to be included in habitats' internal atmospheres and it needs to be made-up periodically due to habitat leakage and airlock usage. The N_2 and argon (Ar) can be obtained by the Mars atmosphere where are respectively at ~2% and at ~3%. While these concentrations are a tiny fraction compared to CO_2, the amount of N_2 and Ar needed may be small enough that separation and collection during propellant production may be adequate. Successful separation may require a cryogenic separation technique and high pressure.

Autonomy is basic on the ability to control excavation operations, both for the minimization of power and maximization of material acquisition and for the management of resource delivery and removal. Autonomy requires the integration of AI systems with sensors for operations and Communication & Navigation Systems to improve autonomy performances and localization. Autonomy system devices must be integrated on rovers and must be able to work in hard conditions as in dusty environments.
Reparation and replacement of component/subsystem failures need specific autonomy systems, these represent a key resource to perform the missions for human long-duration presence.

Resource Processing for Production of Mission Consumables

Regarding regolith processing to extract oxygen and water, autonomous operations and multi-step processing need to be established and demonstrated in a relevant environment. Loss of transferred regolith, reactant, and extracted resources must be minimized. Demonstrating long-duration operations with minimal performance degradation will be critical. Two critical factors in the design and development of regolith processing to extract oxygen systems are the temperature at which regolith processing occurs and/or the reactivity of the processing reactant with reactor materials. If regolith processing occurs at elevated pressures (ex. 15 psi), then valving for feeding and removing abrasive material with no/minimal gas losses will be needed. Several technologies for oxygen extraction from regolith are under development but still require significant advancement before they can be incorporated into a flight demonstration.

Regarding water processing, water electrolysis systems need to operate for long durations, in a low gravity environment, and systems for capture and storage must be optimized. Significant experience exists already for water electrolysis and separation systems for ISS, but operation durations and rates need to be increased significantly. Also, the water processing systems need to be able to remove or mitigate contaminant corrosion and performance degradation. Work has been initiated for both water contaminant removal and contaminant tolerant water electrolysis.

As for CO_2 processing to obtain oxygen, methane (and water), carbon, and hydrocarbons through chemical reactions, conversion efficiency must be optimized. Advancement of CO_2 electrolysis has occurred due to the development of the MOXIE manifested on the Mars 2020 Perseverance rover and through subsequent development efforts. Production of methane/hydrocarbons will not only require scale-up of previous space-related Sabatier and Fischer-Tropsch reactors but also efficient hydrogen/gas and water/gas separations and recycling. If biological processing is considered, complex infrastructures must be established.

Processing performance must be characterized both in terms of product mineral/chemical content and in terms of their quality by specific instrumentation. All the reagents and products must be purified from contaminants

Resource Processing for Production of Manufacturing and Construction Feedstock

Acquisition via excavation and transport are prerequisites for regolith handling. Synergy and commonalities with resource excavation and transport for mission consumable production will need to be evaluated. If oxygen or other contaminants have to be removed and size/type sorting are necessary, a multi-step process may be required.

Regarding regolith processing to extract metals, complex reactant regeneration and metal separation steps in a vacuum are required. Metal extraction processes based on electrochemical reactions also require the provision of sufficient amounts of power for the needed process duration, as well as the design of systems which can sustain prolonged contact with high-temperature regolith and potential corrosive by-products. Work is advancing for both molten regolith electrolysis and molten salt electrolysis technologies. For silicon extraction by ionic liquid, the preparation of task-specific ionic liquid is required. In addition, if the silicon is targeted for solar array manufacturing, preparation of photovoltaic grade silicon wafers or vacuum deposition of silicon onto prepared surfaces is required.

Resource processing to produce plastics typically require complex and multi-step methods, with a conversion efficiency of precursors much lower than 100%. Moreover, initial demand for product will most likely be significantly less than the infrastructure required for production. Initial plastics produced will need to balance the complexity of the production process versus the performance of the plastic for the intended use.

Civil Engineering and Surface Construction

Natural terrains have a complex shape, and substantial changes to the existing conditions will most likely be required to make the site habitable and functional. Architects and engineers require detailed information on the site, as high-resolution 3D terrain model, and on the existing environmental conditions, like insolation or winds (as in Mars case), and in-situ subsurface investigation to design bearing capacity and foundation evaluation. The whole set of this information with a plan of desired/improved conditions are needed to prepare projects of habitable/working infrastructures. Finally, a master development plan can be derived for how the changes are implemented and maintained over time.

The terrain shaping preparation is functional to the final use. To mitigate risk and achieve high reliability, landing/launch operation sites need to be very level and cleared of rock areas. Before construction of structures and habitats, surface areas will need to be cleared and stabilized to ensure efficient and strong construction operations. Rocks have a significant interference with construction activities, regolith surface may need to be stabilized through compaction, binding, and/or sintering to ensure construction stability of landing pads, roads, and structures.

For below-grade investigation and operations, small slot trenches can be created by excavators for prospecting and resource evaluation. Larger trenches can be created to mine the ore once it has become a proven reserve. Trenches also have scientific value as the side walls can be examined by specialized instruments. Below-grade excavation is desired for site preparation to re-distribute regolith to achieve the desired terrain state. It is desired for creating regolith shielding for habitats, equipment, and nuclear reactors. Regolith berms could be used to prevent or mitigate dangerous events like blast/eject materials of high-velocity materials as in landing operations. Roads construction on continuously used pathways and between landers and habitats/infrastructure and between resource sites and processing plants will be needed as surface activities increase. The abrasive effect from large concentrations of regolith, on the equipment and instrumentation, needs to be mitigated in all phases of the construction process. Gas losses for the pneumatic transfer needs to be addressed and gas recycling processes need to be implemented.

The harsh radiation environment on the lunar surface, especially from Galactic Cosmic Rays (GCR) requires significant shielding for long-term human occupation. This could be achieved through vertical construction and shielding or underground structures. Excavation and burial of habitats/structures with several meters of regolith above the structure are methods to allow for significant radiation shielding. Construction processes based on additive manufacturing could have some relevant performance and a flexible approach to the researched solutions but the final quality product is strictly linked to the sintering-melting process that requires very tight control of the energy applied. Alternatively, additive manufacturing processes involving binders will likely require the shipment of large quantities of such binders from Earth, which may prove unsustainable for large-scale construction. The layer-by-layer process construction may limit the architectural opportunities and appropriate solutions for windows, doors, and other protrusions are required to be developed. Brickmaking by temperature and press processes may allow for high control of the manufacturing process and material properties of the constructed object. However, the size of the brick will be constrained compared to additive manufacturing techniques and the brick approach involves a large number of joining operations. An appropriate combination of these two techniques needs to be developed to reduce their limits. Construction methods may induce porosity or gaps in joints that would allow gases to escape if pressurized. A post-construction lining may be required to ensure pressurized structure integrity as well as an extra barrier for safety associated with human occupation. A post-construction liner may also be required for thermal management of interior volumes. Work is advancing on additive construction techniques, especially 3D regolith/binder or concrete-based printing, however, the majority of the work has been performed under terrestrial conditions.

Use of lava tubes could be a possibility for surface habitation. This concept was not strongly considered in the report since it is highly dependent on the location (especially with respect to resources of interest), ease of access, and interior conditions of the lava tube. Use of a lave tube may also require surface clearing/levelling, wall support, and construction of new entrances. While this may be a long-term solution to sustained human lunar surface activities, it was not considered as a likely scenario during initial phases of human lunar exploration.

In-Space Manufacturing

In-Space Manufacturing includes all production processes involved in the manufacturing of goods in the space environment. Only In-Space manufacturing from ISRU-derived feedstock is considered within scope in this gap assessment exercise.

Manufacturing of items from regolith involves techniques similar to the ones studied for regolith-based construction. This includes additive manufacturing based on sintering/melting and additive manufacturing techniques involving binders. Studies have been conducted on selective laser sintering and stereolithography-based additive manufacturing of regolith, which offers adequate levels of resolution and geometrical accuracy for part manufacturing. However, those techniques have only been demonstrated in a terrestrial laboratory environment. The effect of the reduced gravity and other relevant environmental characteristics on the manufacturing process and the products' properties needs to be investigated. The techniques studied so far also involve in some cases significant amounts of power for regolith processing or part post-processing (e.g. green body sintering). Optimisation of the processes, to reduce power requirements is needed. A wider range of regolith processing methods, providing suitable part accuracy should also be investigated. This includes net shape forming, which has not been extensively studied for regolith.

While fibre drawing from regolith simulants has been the subject of several studies, the combination of fibres with a selected matrix and their application for composite parts manufacturing remains to be investigated and optimized.

Additive manufacturing systems for metals and polymers are the subject of intense activity on Earth. Several systems have been implemented or are being developed for application in microgravity, on the International Space Station. Such systems lay the principles for in-situ additive manufacturing equipment to be used to produce items in lunar or Martian exploration missions. However, metal and polymer feedstock derived from ISRU may not offer the same purity or geometrical accuracy as the powder or wire feedstock designed for terrestrial or microgravity systems. In addition, the lunar or Martian partial gravity needs to be accounted for in the optimisation of the process parameters. Therefore, metal and polymer additive manufacturing systems optimized for application in an ISRU context should be designed, from the knowledge gained from terrestrial and microgravity setups. This includes systems that are able to process mixtures of regolith and polymers or metals.

Similarly, subtractive manufacturing systems are currently being developed for the ISS, for instance in the context of the NASA-led Fablab, which will offer metal machining capability. Application of such concepts in the lunar of Martian context, on ISRU-derived feedstock, should be investigated.

Metallic feedstock derived from regolith, e.g. as a by-product from oxygen extraction, could—depending on the reduction process—be in the form of a complex alloy or separated metallic elements. The properties of the obtained material and their processability for part manufacturing need to be assessed.

The use of regolith as support to manufacturing processes, e.g. as mould and die material for casting and forming of metals and polymers, should continue to be investigated.

While most development efforts have been dedicated to processing techniques, joining and assembly of ISRU parts have not been extensively investigated. This could constitute an important enabler for the in-situ manufacturing of complex systems.

Process monitoring and part verification is a relatively young field of activity for in-space manufacturing applications. This should be developed for ISRU-based manufacturing techniques. It becomes particularly relevant for manufactured articles featuring complex or functionally graded structures.

The impact of the lunar Martian environment on the properties of the manufactured parts should also be assessed, in order to ensure that these parts can fulfil their duty in the context of a long-term exploration mission.

To enhance the sustainability of in-situ manufacturing activities, the possibility to recycle ISRU-derived manufactured parts should continue to be investigated, as well as the impact of multiple recycling of the parts' properties and material processability.

CROSSCUTTING CHALLENGES

In order to enable future ISRU missions and to perform all identified operations, robust and reliable systems are needed, capable of withstanding the demanding lunar environment. Considering this, different challenges, relevant for multiple aspects and mission destinations, have been identified and analysed:

Power Generation and Storage

ISRU processes can be extremely power-intensive as well as needing to be performed in challenging locations and environments. Several power generation technologies have been identified for ISRU and space applications: 1. solar thermal, 2. electrical (solar arrays for sunlit operations, batteries and recharging for mobile platforms, fuel cells for lunar night), 3. power for PSR (nuclear fission, radioisotope, power beaming). Devices for power generation are differentiated in cases of "polar missions" and "non-polar missions".

Low grazing angles of sunlight at the pole regions require solar arrays with rotational tracking, preferably on a high mast, or nuclear power systems on the surface. The applicability limits and convenience of energy production, storage, and transfer for hardware with PSRs for stationary and mobile units, internal power (nuclear) vs external power (solar, laser, microwave beaming) have to be demonstrated.

In near-permanently lit locations of non-polar missions will require very efficient and performing deployable solar arrays or nuclear power systems on the surface. Energy storage and availability of particular concern is providing power through the lunar night or Martian storms, demonstrating solutions for energy production and transfer in equatorial lunar day/night (28 day) cycle or for all the duration of Martian global storms, generally not predictable.

System Autonomy

Technologies for Autonomous Operation need to be demonstrated and validated. Operation facilities that enable ISRU hardware to operate with no crew present and minimal or no support from human control. This includes communication needs, situational awareness, failure recovery, and remote maintenance capabilities. Sensors and dedicated hardware/software devices need to be demonstrated. Robotic systems operating autonomously need to communicate and cooperate among them and with the central control system. Advanced computing capabilities will also most likely be required. Robotic systems having a high level of failure recovery and maintenance need to be developed: the availability of specific hardware modules inside them and/or also through collaborative actions of other robots is relevant.

Dust Mitigation

Dust mitigation strategies for hardware are important for ISRU hardware life/performance. Dust mitigation strategies to mitigate dust due to landers and surface movement may be tied to In-Situ Construction. Test conceptual mitigation strategies for hardware interactions with lunar fines to reduce dust prevalence need to be performed with high accuracy. Ejected regolith velocity, departure angles, and energy in engine plume exhaust need to be measured in-situ to better understand mitigation strategies, such as landing pads/berms, and separation.

The ISRU gap assessment team recognizes that this is a critical topic and deserves a dedicated detailed assessment. In 2016, the ISECG Dust Mitigation gap assessment team produced a report on this topic, and it is planned that a supplement edition will be produced to address the key criticalities related to dust behaviour and potential mitigation strategies and technologies.

Surface Mobility and Trafficability

ISRU requires several different mobility approaches for different aspects/phases of ISRU. Resource assessment requires mobility over various terrain features and environments. Resource excavation and civil engineer/surface modification most likely require high surface traction platforms over moderate terrain features. Regolith and product delivery will most likely require repeated traverses over well-established pathways. In all, surface mobility and trafficability finalized to planetary exploration and colonization will require a certain degree of autonomous surface navigation. The ability to remotely traverse over long distances (lifetime vs linear) implies the need to perform pre-positioning of assets and to conduct robust robotic precursor missions. This is needed to demonstrate autonomous surface-navigation: minimize communications/Earth control for resource mapping, transfer to/from resource location to processing location. In general, a planetary surface trafficability modelling needs to be demonstrated: planetary-technical testing (especially trafficability) of prototype or test hardware in high fidelity regolith simulants for each specific case (Lunar and Mars regions).

Trafficability is defined as the capability of the terrain to provide mobility of a particular vehicle. In-situ measurements are key activities to demonstrate planetary surface trafficability. For this aim, the characterization of geotechnical properties and hardware performance need to be tested during regolith interactions and conducting trafficability experiments in polar, pyroclastic, and young impact melt terrains. Demonstrate trafficability inside/outside the PSRs and ingress/egress of PSRs and craters is another key activity, in all the possible cases as potentially low density or low bearing strength surface material, poor lighting conditions, large slopes, etc.

Modularity/Standardization of Hardware (recovery, disassembling, and reuse)

Develop, demonstrate and validate hardware using a well-defined degree of standardization and modularity is at the base of a more efficient strategy to implement processes of recovery, disassembling, and reuse. Standardization can assure the possibility to use the same hardware sections with specific functions to different instrumental applications avoiding the problems coming from operational standards like cable interconnections, power supply specifics, and management-interconnection software. Commonality and standardization of attachment interfaces and parts could also be extremely beneficial for high wear items and applications. Modularity facilitates upgrades and recovery actions, as it permits to disassemble more easily the functional hardware sections and to verify the possibility to reuse the working hardware sections.

Cryogenic Fluid Production, Management, and Transfer

Demonstrate the applicability of technologies using chemical-physical processes for the gas of interest extraction and storage (liquefaction) for the Surface Cryogenic Production and Management (Storage & Transfer). High-pressure compressors with high-pressure tanks need to be adapted and used for High-Pressure Gas Storage and Transfer. Specific processes and devices for liquefaction, zero-loss storage, and zero-loss transfer H2 need to be demonstrated, starting with the most relevant production of gasses like O_2, CH_4, and H_2. Standardization of interfaces and fluid couplings is also essential for multiple applications and customers of the products (landers, fuel cell power systems, habitats, rovers, etc.)

Life Support and Habitation Systems

Habitation Systems will need to be designed and tested for micrometeorite protection technologies: the knowledge of the predicted average micrometeorite dose at the expected landing polar location is the base of any shielding application. A second step is the direct measure of micrometeorite shielding performance of bulk regolith and constructed materials.

Another important aspect of Habitation Systems is radiation shielding technologies. To test protecting human crews beyond the magnetic fields of the Earth from space radiation is critical. Testing radiation shielding technologies and operational approaches, are strongly required. It is applied for the shielding aim a detailed knowledge of the predicted average radiation dose from GCRs and SPEs at the expected landing polar location. Also relevant is to measure the radiation through bulk regolith, constructed materials, water, and in-situ produced plastics.

Model-based engineering tools (e.g. static and dynamic simulators, metrics) incorporating data, knowledge, models related to the processing of In-Situ Resources for the production of Life Support consumables are required to design optimum Life Support system architectures per ISRU mission scenario. Starting from good practices of circularity, it is anticipated that regenerative LSS (including reuse, recycle, upcycle approaches) will contribute to mission sustainability in the first place. As 100% circularity is not achievable though, provision of LSS consumables directly, or of intermediate products, thanks to ISRU, will definitely play a role, as an interesting alternative to potential resupply from Earth (if ever possible). Additionally, the various kinetics and other characteristics of regenerative LSS and ISRU technologies shall allow for smart combinations of technologies, depending on the specific mission design (e.g. location, duration, crew size). It should also be noted that since Life Support Systems and ISRU both process CO_2 and H_2O, there are opportunities for developing and using common technologies, though the scale of operation for ISRU may be 1 to 2 orders of magnitude larger.

Whether Mars or Moon will be the destination, resources/products of interest for LSS such as water, oxygen, carbon dioxide, and nitrogen will consistently be present, either in the local environment, or linked to the crew. Associated processing technologies will invariably be building blocks of any LSS, possibly with more or less importance and impact.

GROUND DEVELOPMENT AND FLIGHT MISSIONS

As with any new technology, before it can be utilized in a mission-critical role for human spaceflight, it needs to have undergone significant ground development as well as demonstrated its performance in the actual flight environment. While the section *ISRU in Moon/Mars Human Exploration*' of this report discusses the proposed phased mission implementation of ISRU into the international human Moon/Mars exploration architecture, this section will discuss the general ground technology and flight demonstration philosophy that will be utilized. The section will also include further information provided by individual national/space agency activities that are underway in separate sub-sections.

To achieve the end goal of using ISRU products for mission-critical applications, such as life support consumables for the crew or propellants for crew ascent from planetary surfaces, space agencies are considering a conservative ground development and flight demonstration strategy for ISRU. This strategy incorporates a four-stage approach:

I. Extensive ground testing at mission-relevant scale under flight environmental conditions and analogue operation conditions,
II. Direct measurement of resources and demonstration of critical technologies in flight,
III. Demonstration and validation of ISRU systems and products at relevant mission scale to extend or enhance a robotic and/or crewed mission (i.e. pilot operation), and
IV. Utilization of ISRU systems and products in a mission-critical role.

In Stage I, space agencies will develop and advance technologies, subsystems, and systems that will acquire and process lunar simulants into mission products at relevant mission scales and under lunar vacuum and thermal environments. Environmental test facilities and simulants that space agencies will use in this development stage are presented in *Test Facility Assessment* and *Regolith Simulant Assessment* sections of this report. Each space agency will pursue ISRU technologies, systems, and flight demonstration activities that best support their agencies' goals and objectives. The *Technology Assessment* section of this report provides information on current ISRU technology development activities being performed by each space agency.

In Stage II, space agencies will utilize orbital and lander missions to better understand the resources on the Moon, especially lunar polar water and volatile resources that are needed to support technology development and eventual site selection for long-term human surface operations. It is anticipated that early lander missions will be aimed at obtaining critical data on lunar regolith and environmental properties that were not obtained from the previous Apollo and Lunar Surveyor missions. Phase II will also perform proof-of-concept and risk reduction demonstrations of critical ISRU technologies and concepts that are most dependent on interacting with lunar regolith and/or need to interact with large amounts of lunar regolith under lunar surface conditions to validate longevity and robustness. Priority and selection of these demonstrations will be influenced by the impact and lunar architecture phase importance depicted in Table 3 "ISRU Strategic Knowledge Gaps" and Tables 5a, b, and c "Human Lunar Exploration – ISRU Objectives".

In Stage III, space agencies will integrate technologies, many of which were demonstrated in Phase II, into an end-to-end system that will produce products at a relevant mission scale and over a relevant mission duration. This stage is again influenced by the ISRU objectives, priorities, and impacts discussed in Human Lunar Exploration Objectives and Human Lunar Exploration Phases sections of this report and depicted in Table 3 and Tables 5a, b, and c.

Initiation of Stage IV will be based on the results from Stages I to III and may include space agencies deploying all the infrastructure required to implement and utilize ISRU products in mission-critical roles. This could include (re-)fuelling crew ascent vehicles and surface hoppers and/or building landing pads and structures for crew and infrastructure protection.

Polar Resource and ISRU-Related Lunar Flight Missions

While a new international human lunar architecture is still in work, it should be noted that individual nations and space agencies are progressing with plans for new lunar orbital and surface missions. While some of these missions have been approved and have expected launch dates, others are only in early stages of planning and budget allocation (refer to the Global Exploration Roadmap Supplement, issued in August 2020, for missions planned by ISECG space agencies). The purpose of this section and Table 10 is to provide readers with an understanding of the potential scope of missions being considered at this time. Missions denoted with dates should be considered approved. Missions without dates should be considered as planned and may be subject to change due to budgets, priorities, and partnerships. Note that even though NASA plans approximately two Commercial Lunar Payload Services (CLPS) missions per year, only the selected missions are shown in the table below since the purpose and payload for the missions are still to be determined. The first two CLPS missions will land in lunar equatorial locations but will demonstrate science instruments that may be important and used in subsequent resource assessment missions.

Table 10. Approved and Planned ISRU-Related Lunar Flight Missions

2020		**2030**
Orbiters *(Resource Assessment)*		
2021 Artemis Cubesats - LunaHMap, Lunar IceCube, Lunar Flashlight (NASA)	2024 Luna 26 (RSA)	
	2025 Lunar Trailblazer (NASA)	
2022 KPLO w ShadowCam (KARI/NASA)		
Landers		
Science & Resource Assessment		
2021 CLPS-1 (NASA)		
2021 Luna 25 (RSA)		
2021 Chandrayaa-3 (ISRO)	2025 Luna 27-PROSPECT (RSA/ESA)	
2022 CLPS-2 (NASA)	2027 Luna 28 (RSA)	
2022 CLPS-3 PRIME-1 (NASA)		
2023 CLPS-4 VIPER (NASA)		
Lunar Polar Exploration (JAXA/ISRO)		
2022-24 Chang'e-6 (CNSA)		
Mission Consumables		
Subscale Ice Demo (NASA)	ISRU Processing Demo (NASA)	
Subscale O_2 Demo (NASA)	ISRU Pilot Plant (NASA)	
O_2 Demo (ESA)	ISRU Pilot Plant (ESA)	
Excavation & Construction		
ISRU Pilot Excavator (NASA)	Construction Demo 2 (NASA)	
Surface Construction Demo 1 (NASA)		

PARTNERSHIP OPPORTUNITIES

Why Partnerships are Important

Recognising that no one agency alone can financially or technically realise all the ISRU goals outlined in this report, a clear opportunity exists to explore how mutually beneficial partnerships can support and accelerate ISRU technology development and deployment. This is an opportunity for the international community to leverage inclusive multi-stakeholder partnerships with common objectives and shared vision, in order to foster international collaborations, develop new partnerships, maximize returns on their coordinated efforts and investments, as well as increase their chances of success. It should be noted that while governmental partnerships are usually between national/international space agencies, broader involvement and partnerships with other government agencies are growing to ensure governments maximize their investments in space and terrestrial technology and development.

While space exploration activities have traditionally been the domain of international and national government agencies, public-private partnerships are now more common than ever. More recently, non-governmental organizations, including industry and the private sector and academic institutions have been increasingly participating in those activities in various capacities; as suppliers of technology, as subcontractors of international and national space programmes, or even as entrepreneurial innovators in commercial space ventures.[2] As described in the earlier sections, ISRU developments and challenges are cross-cutting, multi-disciplinary, and benefit from the engagement of the broader community, across discipline groups (ex: AI, Robotics, Construction, Geology, Mining), public sector (ex: space agencies, research institutes) and private sector entities (ex: ranging from well-known multi-nationals, down to new start-ups). New innovative partnership mechanisms among these entities are encouraged.

The importance of partnerships was previously identified in two previous ISECG reports

- ISECG Telerobotic Control of Systems with Time Delay Gap Assessment Report (2018)
- ISECG Autonomy Gap Assessment Report (2020)

Collaborative Approaches

The ISRU strategic knowledge gaps outlined in Table 3 and the missions in the planning stage depicted in Table 10 provide prospects for Agency-led collaborations to cooperatively mature technologies and advance capabilities in a well-defined manner. A number of practical approaches can be explored by Agency partners to assess opportunities and formulate plans towards collaborative technology development. Such collaborative and inclusive approaches provide an opportunity for capacity-building in countries/organisations with emerging capabilities, encouraging creativity, innovation, and entrepreneurship; thus, further encouraging the incremental build-up of capacity to meet our ISRU technology needs. Some practical approaches include:

1) Planning and Coordination

Partner agencies can coordinate on a) monitoring the progress of technology development and demonstrations, b) communicating technology advances, and c) updating the mission scenario and concepts of operations as technology gaps related to ISRU are realized.

2) Shared Insights and Information

Partner agencies can facilitate conferences, workshops, and seminars on ISRU technologies and establish new (or utilize an existing) secure joint online data repositories to share data, papers, reports, and insights gained through related technology development stages. Open sharing of space data and simulations (especially where funded by public money) is encouraged to promote collaboration and partnerships.

[2] United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS), 61st session, General Assembly, "Global Partnership in Space Exploration and Innovation"

3) Coordinated Research Agendas
Partner agencies have a significant opportunity to maximise ISRU technology developments and minimise duplicated efforts through well-coordinated research objectives, fostering participation in joint programs and projects, and ideally, agencies securing agreements for specific concept development. Where feasible, agencies, industry, and academia can seek partnerships with national, regional, or international research institutions to collaborate on a common ISRU objective. Space agencies can catalyse anchor partnerships to establish Research and Technology Organizations (RTOs) to strengthen synergistic opportunities. RTOs are innovation hubs that aggregate expertise, enable community-building initiatives, advance knowledge-based design with transversal research and development values.

4) Specific ISRU System Development
Partner agencies can promote and participate in joint programs/projects, coordinating performance and design objectives, roles/responsibilities, and schedules to minimize duplication and maximize progress. Partner agencies can also collaborate on requirements definition, and coordinate on the minimum set of standards and the minimum set of data needed to a) enable development and test, b) facilitate integration, c) ensure trades, benchmarks and demonstrations are relevant, d) minimize rework, and e) ensure future mission infusion, such as joint operations capabilities. The design and standardization of system interfaces would not only strengthen collaboration at the technical level, but helps to ensure sound system development, interoperability, and ultimately, mission success.

5) Access to and Joint Activities at Planetary Field Analogues for Testing
Partner Agencies can identify and assist in coordinating access to respective terrestrial analogues to provide new options for validation and verification of ISRU systems and components in field conditions. These types of analogue sites could have applications in human operations, robotic operations, or cobotic operations. Inter-agency or international collaborations can be leveraged to widen access to analogue sites for operational ISRU systems testing. For example, Devon Island, Haughton impact crater, is an analogue site prominently used for astronaut training by CSA and NASA (human-computer interaction of interest in the context of ISRU and human lunar surface activities). ESA equally makes use of natural planetary field analogues within its member states territory and in international partnership, in particular in the scope of EAC's Caves and Pangaea programmes for astronaut training, and various robotic field trials as part of the ExoMars and Sample Fetch Rover programmes. Analog sites can be used to further joint development and integration of ISRU hardware and operations as well. For example, NASA and CSA utilized analogue field locations in Hawaii in 2008, 2010, and 2012 to demonstrate ISRU hardware and integration under simulated mission conditions.

Agency Partnership Opportunities

<u>ASA/CSIRO – Australia</u>

A key element of Australia's national strategy for space technology development is to cultivate partnership opportunities with other national agencies and the private sector, including Australia's mature mining sector. Via the ASA, Australia is closely engaged with NASA to deliver new technologies that support the Moon to Mars initiative. CSIRO is currently funding a major Future Science Platform program focused on the development of Space Technologies, and a key project within this initiative is specifically targeting ISRU and lunar foundation services. With regard to the mining industry, a key area of focus is on the development of ISRU technologies that will also enhance the productivity of terrestrial mining.

<u>ASI – Italy</u>

ASI interest in ISRU related technologies is increasing and the present objective is to map national capabilities and expertise, supporting the most promising ones with institutional funds or by ESA (via Italian contribution) and looking at future international collaborations.

CNES – France

At the French level, we are preparing an "ISRU roadmap" based on co-building approaches via workshops and other contacts with: French industry, SME's, start-up, and research laboratories, to be able to identify specific ISRU activities (for example: gas purification and storage, …). Targets are to better identify French expertise and select within this expertise those requiring to increase their level or TRL with institutional help with CNES funds or ESA level (via French contribution). All these should and would be open to potential international collaborations. For example, France has a long term and large experience in the "sample analysis" domain starting from historical Moon sample analysis and more recently developed via Curiosity (SAM-GC), Perseverance (SuperCAM), ExoMars (MOMA-GC). It could be among other a way of future collaboration.

CSA/NRCan – Canada

Canada has been involved for many years in the development of ISRU systems, in particular in the fields of rover, drilling, and excavation systems as well as avionics and navigation and autonomous guidance software, sensors, and instruments. These developments have benefited from industry participation on multi-national missions. It is envisioned currently that a micro-rover with ISRU related instruments is expected to launch on a NASA CLPS mission. These precedents have evolved over the years as the CSA continues to strengthen strategic planning and partnerships to expand the development of exploration technologies. It is also envisioned that ISRU-related future activities will progress in-line with the phased approach discussed in this document.

The aim of the Canadian Minerals and Mining Plan (CMMP) is to capitalize on opportunities to strengthen Canada's competitive position within the global mining sector. The Government of Canada and Natural Resources Canada (NRCan) can help facilitate opportunities to connect with Canada's world-leading mining sector to explore opportunities to advance R&D, innovation and to solve today's grand challenges on Earth and in space. In addition to mining firms and the services and suppliers sector, the CMMP also looks to raise awareness with provinces and territories and bring key players within and outside the mining innovation ecosystem to explore new partnership opportunities.

DLR – Germany

Germany has established and is open to new partnerships within different frameworks, trying to bring forward key capabilities to the respective mission's portfolio.

ESA – Europe

The exploration cycle in LEO is complete thanks to significant investments and strong international collaborations by partner agencies at the ISS. The next destination for extending human exploration will be cis-lunar space and it is already under development with the Gateway, again strongly dependent on international collaborations. The following cornerstones are the surface of the Moon and eventually also Mars, and for those distances, it is no longer sustainable to bring all resources from Earth. ISRU can be a strong leverage to support sustainable surface operations for crew and perhaps for civilisation.

In ESA, partnership opportunities for Moon surface exploration are very much welcome as a logical follow-up to the successes in partnering at the ISS and upcoming Gateway missions. The ESA Exploration Programme Executive and Member States continue to jointly define a strategy for exploring together within Europe and also worldwide with its international partners.

JAXA – Japan

Space exploration is an international endeavour difficult to achieve by a single agency only. JAXA is always looking for opportunities for collaboration with international partners. The example includes participation in NASA's Artemis lunar program which aims to human land on the Moon, and LUPEX mission which is joint lunar polar exploration with ISRO to work on the investigation into a lunar rover and lander that will explore the south pole of the Moon.

KARI/KICT/KIGAM – South Korea

KARI is closely collaborating with national research institutions including KICT and KIGAM in ISRU area. KARI is persistently pursuing international collaborations and closely cooperating with NASA in the moon program. Korea's KPLO will be launched by August 2022. The six instruments including NASA's Shadowcam would contribute to the investigation on ISRU prospecting for both polar and other regions. KIGAM will focus on providing elemental maps for lunar geology and resource investigations. NASA selected 9 participating science teams for KPLO. The outcome of NASA Participating Scientist Program (PSP) on KPLO mission would maximize future scientific contributions by Korea toward the international cooperation on lunar explorations. KASI is supposed to deploy a few science payloads to the lunar surface through NASA CLPS program in the mid-2020s. ISRU collaborative research and development can be extended under the bilateral or multilateral cooperation framework by catching rideshare for lunar landings such as CLPS or Artemis and so on.
On the other hand, KICT is ready to provide collaborative tests using its DTVC facility to domestic and foreign ISRU communities who are willing to have their own ISRU equipment in need of simulated lunar environmental tests.

LSA – Luxembourg

In the frame of the European Space Resources Innovation Centre (ESRIC), international partners with a strong interest in this field are welcome to join ESRIC in the near future to develop new ideas and projects.

NASA – USA

Establishing and leading partnerships is one of NASA's key foundations in its strategic plan. The importance of partnerships is further emphasized in the US Space Policy Directive-1 which states, "Lead an innovative and sustainable program of exploration with commercial and international partners to enable human exploration across the solar system and bring new knowledge and opportunities back to Earth". While NASA is leading the Artemis program, the US looks to have international partnerships play a key role in achieving a sustainable and robust presence on the Moon while preparing to conduct a historic human mission to Mars. To help guide in the discussions, the US has initiated the Artemis Accords with international partners to 'establish principles for a safe, peaceful, and prosperous future.

UAESA – United Arab Emirates

The UAE Space Agency has a large number of agreements across different space agencies to support and participate in international collaboration missions and always looking for opportunities to cooperate with international partners. The UAE was proud to be among the handful of countries that helped to draft the Artemis accords and signed it and now looking forward to further discussion to become an enabler of the program.

UKSA – United Kingdom

Space exploration is an inherently cooperative endeavour and the UK already engages internationally with ESA and through bilateral agreements. We welcome the opportunity to expand national capabilities through international partnerships and exploration missions.

PRIVATE SECTOR INVOLVEMENT

Government space exploration programs have always relied on private sector involvement to support technology development and contribute to mission success. Past observations and studies have demonstrated the value of the commercial space sector and the benefits of private sector involvement. For example, Robert S. Walker, former chairman of the US President's Commission on the Future of Aerospace and former chairman of the U.S. House Science Committee noted that the case for commercial space is very strong and the private sector must become a prominent player in our space future where a robust space industry requires greater reliance on nongovernment investment and entrepreneurial vision[10]. Similarly, Brian Weedon noted that over the last decade, there has been a revolution in the commercial space sector based on a potent combination of Moore's Law and spin-in technologies from the information technology sector driving the creation of new space companies and creating an infusion of fresh ideas, new approaches, increased innovation, and renewed excitement in the space world[11].

Private space companies are becoming more than the typical contractors for government space activities. Instead, they are bringing external investment, technologies, and partners into mostly government-funded efforts to provide critical products and services for robotic and human exploration. For example, Nokia has announced details after being named by NASA as a partner to advance "Tipping Point" technologies for the Moon, deploying the first LTE/4G communications system in space and helping pave the way towards sustainable human presence on the lunar surface. Nokia Bell Labs' pioneering innovations will be used to build and deploy the first ultra-compact, low-power, space-hardened, end-to-end LTE solution on the lunar surface in late 2022. Nokia is partnering with Intuitive Machines for this mission to integrate this ground-breaking network into their lunar lander and deliver it to the lunar surface. The network will provide critical communication capabilities for many different data transmission applications, including vital command and control functions, remote control of lunar rovers, real-time navigation, and streaming of high-definition video. These communication applications are all vital to long-term human presence on the lunar surface[12].

In addition to the general contractor model, alternative approaches are also emerging. For example, the government of Luxembourg has focused on promoting and supporting commercial space activities, with government activities typically undertaken in support of private space companies. This approach has been successful for Luxembourg as demonstrated by its status as a major player in the satellite communications business and, due to its SpaceResources.lu initiative, declaring space as an economic pillar has now attracted numerous companies to open offices within the country in relation to ISRU[13]. The Luxembourg Space Agency encourages hereby the use of ISRU technology for terrestrial applications and cooperation with terrestrial companies. An example is Maana Electric, a space and renewable energy start-up focused on dual applications of space technologies for terrestrial and space purposes. The company is focused on the utilization of ISRU technologies for the localized production of solar panels using desert sand (on Earth) or regolith (in space). Similarly, iSpace Europe cooperates with terrestrial companies to develop technologies that add value to both lunar and terrestrial industries.

In 2018, the LSA published the results of a study on the future markets and value chains of ISRU[14]. This study includes an estimation on technology spillover effects, representing effects coming from the technological developments associated with the Space Resource Utilization (SRU) value chains which are expected to encompass several technical domains such as materials science, manufacturing, additive manufacturing, robotics, and data analytics, but who are not directly linked to users of the SRU-enabled services. The study concludes that a conservative estimate of the spillover benefits is €2.5 B over 50 years (Present Value, 2018).

In 2020, Luxembourg entered a strategic partnership with the European Space Agency (ESA) to create a "European Space Resources Innovation Centre" (ESRIC), which will partner with public and private international players in this field to create a hub of excellence for space resources in Europe. ESRIC's activities will focus on space resources research and development, drawing together excellence from public research and its facilities, with private sector initiative and efficiency. The centre will also contribute to economic growth by supporting commercial initiatives and start-ups, offering a business incubation component, and enabling technology transfer between space and non-space industries[14].

In the United States, the importance of public-private partnerships (PPP) and private investment in space exploration and infrastructure has grown significantly over the last decade. The first major step was the initiation and establishment of the Commercial Orbital Transportation Services (COTS) program, to deliver cargo and supplies to the International Space Station (ISS) after the US Space Shuttle was retired. With the success of the COTS program, the Commercial Crew Program (CCP) was initiated to launch astronauts to the ISS from the US, and successfully delivered crew to the ISS for the first time in 2020. The involvement of PPP in critical space exploration roles has further expanded to include delivery of payloads on robotic landers as part of the Commercial Lunar Payload Service (CLPS) program, Gateway elements and logistics, and delivery and return of crew as part of the Human Landing System (HLS) program. Along the same lines as the Luxembourg ESRIC, the John Hopkins Applied Physics Lab (with funding from NASA), has initiated the Lunar Surface Innovation Consortium (LSIC). The purpose of the LSIC is to foster and promote the involvement of industry and academia into NASA and commercial space activities, with a focus on the six main elements of NASA's Lunar Surface Innovation Initiative: ISRU, Surface Excavation and Construction, Sustainable Power, Dust Mitigation, Extreme Access, and Extreme Environments

An important trend in this approach is the involvement of non-space departments or agencies who are seeking to benefit from these partnerships with greater industry involvement from both space and non-space firms. For example, NASA and the U.S. Department of Energy will seek proposals from industry to build a nuclear power plant (i.e., fission surface power system) on the moon and Mars to support its long-term exploration plans. The goal is to have a flight system, lander, and reactor ready to launch by 2026. According to Anthony Calomino, NASA's nuclear technology portfolio lead within the Space Technology Mission Directorate, "the ability to produce large amounts of electrical power on planetary surfaces using a fission surface power system would enable large-scale exploration, the establishment of human outposts, and utilization of in-situ resources while allowing for the possibility of commercialization"[15].

In Australia, UNSW Sydney signed a Memorandum of Understanding (MoU) with Japanese lunar exploration company iSpace in 2020, to jointly pursue research and development in space resources and infrastructure. This MoU will enable UNSW and iSpace to work together on areas of common interest, including technology development and space missions. UNSW was seen as a key partner for iSpace to help realise its vision to create a lunar economy underpinned by the use of space resources. UNSW and iSpace will also work together on aspects of the federal government and Australian Space Agency's Moon to Mars initiative, including scientific investigation using mineral and other substances of the moon. Profs. Dempster and Saydam from UNSW have been long-term advocates of Australians mining in space and believe space resources is an area where Australia should be looking to have an advantage by exploiting its large mining companies, strong mining engineering research, and leading mine automation[16].

In Canada, the Department of Natural Resources Canada (NRCan) has engaged with the mining industry and Canadians on the future of exploration and mining through the Canadian Minerals and Metals Plan (CMMP). This national conversation identified the need to promote collaboration across industries to maximize R&D efforts and develop solutions to the grand challenges of today by looking to other high-tech industries and new frontiers to build Canada's mines of tomorrow, including the space sector. This has opened the door for greater collaboration between NRCan partners in the mining industry and the Canadian Space Agency (CSA), in a concerted effort, leveraging Canada's Space Strategy. A whole-of-government approach is enabling cross-cutting efforts to better understand common innovation challenges, the potential for investment and economic growth, and opportunities for Canadian industry to develop spin-ins and spin-offs between sectors.

As the Government of Canada is planning for the next phase of human and robotic space exploration, an important aspect of these future missions is the ability to use resources in space, such as regolith mined on the surface of the Moon to provide the necessary resources to astronauts. As part of Canada's research on this topic, the CSA is undertaking a study to better understand the dynamics of a future space resource utilization market and potential benefits to both the space and terrestrial mining sector. The study will provide a description of the general business case for space resource utilization, including an overview of the short-term and long-term potential market, and how the market is expected to evolve over time (including market size, customers, technologies, ISRU vs. SRU, timeframes, etc.). The study will focus on the business case for resources used as rocket propellant since this is believed to be the most near-term application. This will include an analysis of the international demand and opportunities while focusing on the Canadian context and potential synergies between the space sector and the terrestrial mining sector. The study will also touch on economic impacts that are expected to emerge such as technology spin-offs for the terrestrial mining sector, for example, in-situ resource development, automation, mobile energy, mining without water, and zero carbon footprint. Other key metrics of economic impact will be explored, such as in the areas of innovation, economic growth, and job creation.

Examples of Potential Spin-ins and Spin-offs

Spin-ins from terrestrial mining to ISRU

- **The space station biomining experiment** – Charles S. Cockell and Rosa Santomartino demonstrates rare earth element extraction in microgravity and Mars gravity. Microorganisms are employed to mine economically important elements from rocks, including the rare earth elements (REEs), used in electronic industries and alloy production. Cockell and Santomartino carried out a mining experiment on the International Space Station to test hypotheses on the bioleaching of REEs from basaltic rock in microgravity and simulated Mars and Earth gravities using three microorganisms and a purposely designed biomining reactor. The data from this experiment demonstrated the potential for space biomining and the principles of a reactor to advance human industry and mining beyond Earth[17].
- **Remote and autonomous mining operations** – Over the past decade, Rio Tinto has become a recognized international leader and has integrated fully autonomous trucks, autonomous drills, and machine learning into various aspects of its Australian operations, utilizing real-time data analytics to track productivity and safety infrastructure covering their network of mining operations, ports and rail system.
- In Canada, Agnico Eagle is accelerating the use of its automated loading and hauling solutions and is adding an automated production drill for testing at its LaRonde mine in Quebec. The goal is to extend the life and current production levels at North America's deepest mine–taking operations from 3.1 km to 3.5 km below ground by 2028. Developments in automating major mining operations, especially those in remote and hazardous environments deep underground or in the Arctic, can provide practical lessons to inform the development of ISRU architecture and its operations. As terrestrial activities become more sophisticated through the use of AI and accelerate the adoption of renewable energy technologies, many parallels could be drawn between ISRU and terrestrial mining.
- **Teck's RACE21™ program** is an important example of how the mining industry in Canada is approaching technology infrastructure renewal, accelerating the adoption of automation and robotics, and enabling advanced data analytics and artificial intelligence–driving sustainability, efficiency, and

competitiveness of the industry. As part of this work, Teck's Highland Valley Copper (HVC) Operations in British Columbia have piloted an autonomous haul truck (AHS) pilot program. Since its launch in 2018, the AHS pilot at HVC has progressed well, increasing productivity and cost reductions to help enhance the feasibility of extending mine life beyond 2027. To date, the HVC AHS fleet has safely moved over 50 million tonnes of material, which equates to over 217,000 loads, and has advanced plans to increase the AHS fleet to 35 trucks out of the 52-truck fleet operating site-wide in support of its proposed extension of HVC's mine life to 2040.

- **Decarbonization technologies and supply chain management**: Rio Tinto, Alcoa, and Elysis joint venture in improving the development of an innovative aluminium smelting cell, minimizing carbon footprint, and enhancing reusability of products. Investors in this initiative include Apple and the Government of Canada, among others. Novel industrial processes can enable translational benefits in the context of ISRU processes comparable to the Metalysis-ESA collaboration.

Spin-offs from space to terrestrial mining

- **Space-based RADAR and mining** – ESA's Harsh Environments Initiative under the Technology Transfer Programme, included a number of past spin-offs into terrestrial mining. A mining application, for example, included the use of radar instruments designed to guide roving planetary vehicles and undertake subsurface exploration was modified to provide enhanced, high-resolution views of operations where visibility is extremely poor[18]. Similarly, ground-penetrating radar developed for space exploration resulted in the development of portable radars to penetrate the ground and produce images of hidden structures and objects. For example, Ginger, a past ESA technology project, set out to develop a ground-penetrating radar in support of a proposed programme to explore the Moon was used by RST Radar Systemtechnik of Switzerland and MIRARCO of Canada to develop CRIS, a dedicated ground-penetrating radar prototype, to detect cracks in the walls and roof of mine drifts[18].

- **Safer Mining** – In a series of projects based on Sensori-Motor Augmented Reality for Tele-robotics or SMART, space-based technologies such as Man/Machine Interface, ground-penetrating radar, loss-less data, image compression, and space robotics, was integrated to control individual machines, while a supervisory system that can simulate particular events was developed by C-CORE to create more efficient deployment of machines by optimising the use of shared resources such as tunnel intersections and rock-dumping sites[18].

- **Smart Memory Alloys** (SMAs) – The European space programme developed SMAs for use as lightweight, temperature-controlled actuators. The unique features showed great promise for a number of other fields such as mining, demolition, and quarrying. D'Appolonia, the Italian member of the Spacelink group with considerable experience in geotechnical engineering, realised that developing the quarrying application would be an ideal project for a European consortium. The company Ripamonti, which had been manufacturing mining equipment since 1970, became a lead partner in an EU-funded CRAFT R&D project. In addition to Ripamonti and D'Appolonia, eight companies from Italy, Spain, Portugal, and the UK also became involved. The team, with expert advice from Brunel University and Duomo (an organisation dedicated to the maintenance of Milan's magnificent marble cathedral), successfully demonstrated that quarrying applications using Shape Memory Alloys could be competitive. Meanwhile, field trials with full-scale blocks of stone have validated the system design under realistic harsh working conditions[18].

- **Rovers** - the Canadian Space Agency (CSA) has worked in collaboration with over 40 Canadian companies and universities to build a team of terrestrial rovers that may develop into a version that explores the surface of new worlds. Ontario Drive and Gear developed ruggedized versions of CSA's Juno rover and a larger 8-wheel robotic platform for applications in defence, mining, and industry. TerraSmart, a Florida-based company, offers robotic ground screw hole installation utilizing the Argo J5 Rover and Provectus Robotics control system to autonomously geo-locate and drill ground screw holes for solar energy fields.

Private Sector Involvement Through Prize Challenges

In the past decade, governments and private businesses have looked to harness innovation by entrepreneurs and SMEs outside the traditional space industry through "prize challenges". The most notable example starts with the Google Lunar XPRIZE, created to (1) spur affordable access to the Moon and give space entrepreneurs a legitimate platform to develop long-term business models around lunar transportation, and (2) to inspire the next generation of scientists, engineers, space explorers, and adventurers to enter the STEM fields.

Government programs that have used the prize challenge model include NASA's Centennial Challenges (initiated in 2005) to directly engage the public in the process of advanced technology development. The program sought innovations from diverse and non-traditional sources. Increasingly, other countries have developed their own programs to develop innovative ways to involve private citizens, entrepreneurs, and SMEs with more flexibility and to manage greater risk outside the traditional contracting model. For example, NASA's "Break the Ice" Lunar Challenge is looking for innovators to design a system architecture to excavate icy regolith and deliver acquired resources in extreme lunar conditions. Canada is also using a comparable model with the Privy Council Office's (PCO) Impact Canada Initiative by working with CSA and NASA on the Deep Space Food Challenge. This is an open call to innovators to develop new food production systems for deep-space exploration, such as space missions to the Moon and Mars. Similarly, for terrestrial mining, Natural Resources Canada (NRCan) launched the CrushIt! Challenge, which seeks to award a grant to small-scale innovators with the biggest energy breakthrough in crushing and grinding rocks (i.e., comminution). Additional opportunities with provinces and territories are also being explored, such as a pan-Canadian initiative on prize challenges for mining innovation under the Canadian Minerals and Metals Plan. CSA and NRCan are engaged with the Impact and Innovation Unit at PCO to address complex challenges, providing additional opportunities for both departments to combine their efforts towards ISRU innovation, facilitated by a whole-of-government approach and Canada's Space Strategy.

As government agencies look at the ambitious goals of returning humans to the Moon and staying there and preparing for future endeavours such as the human exploration of Mars, the private sector will likely be a larger contributor and potentially, leaders in advancing space exploration beyond traditional partnership models with governments and their space agencies. The following provides examples and an understanding of how each country/government agency is considering traditional and alternative approaches to private partnerships in relation to ISRU.

<u>ASA/CSIRO – Australia</u>

The ASA is currently offering a significant funding opportunity to the Australian industry under its Moon to Mars initiative. Program opportunities range from the initial "Demonstrator Feasibility" grants to a more extensive "Demonstrator Mission" opportunity.

<u>ASI – Italy</u>

ASI is currently interested in ISRU related technologies and is mapping national industrial capabilities and expertise, with the aim of supporting the most promising enterprises with institutional funds or by ESA (via Italian contributions).

CNES – France

CNES is looking forward to becoming a key player in future scenarios of long-term missions in space, we have many initiatives to federate industry and research around the ISRU topic, like:

- ***"Objectif Lune" group*** led by the « Association Nationale Recherche Technologie » to coordinate French initiatives,
- ***"Spaceship FR"*** (included in the ESA Spaceship network) project located at CNES Toulouse which is a lunar/martian mock-up of a base at scale 1 to develop new technologies and to increase their TRL.
    - Objectives:

      To provide technical means to create new, innovative & disruptive systems, while also gathering assets from Sciences, Research, Universities, and Industries into the same melting-pot.

      To be designed and built motivated by future missions to the moon and mars.

      To foster collaboration between partners and CNES in all space sciences/technologies and operations, along with joining ESA's current network of spaceships.
- ***Space'ible:*** The space prospective observatory aims to understand and share current and future developments in the space field as well as to imagine and build possible futures. The objective is to inform decisions about desirable futures within the range of possible futures, in particular by recommending concrete activities in the short/medium term.

In parallel to these programme frameworks, we try to increase the involvement of companies about ISRU activities which are not included in the historical core space activities but instead related. For example, we develop activities with ALAT (Air Liquide Advanced Technologies), and COMEX about gas treatment and life support. And the aim is to attract and involve more and more non-space companies. We will help them to derivate their Earth business to the space constraints for a new business in ISRU.

CSA/NRCan – Canada

The Lunar Exploration Accelerator Program (LEAP) was created to provide a wide range of opportunities for Canadian science and technology activities in lunar orbit, on the Moon's surface, and beyond. LEAP is looking to foster innovation in areas of strength for Canada, like artificial intelligence, robotics, science, and health. It will support the commercialization of innovative ideas from the Canadian industry, including small and medium-sized businesses, in order to help them become an integral part of the growing new-space economy. The scientific and technological advancements stemming from LEAP are expected to generate tangible benefits for Canadians in their everyday lives.

The Space Technology Development Program (STDP) is a well-established funding program, supporting innovation, research, and development for the growth of Canada's space industry. Not only does this program help position Canadian companies to participate in international missions, it generates commercialization opportunities and broader socio-economic benefits. Contracts are issued to Canadian organizations for the development of technologies to support future needs of the Canadian Space Program, while non-repayable contributions are awarded to Canadian organizations to support the development of innovative technologies with strong commercial potential.

DLR – Germany

DLR since 2013 conducts annually the INNOspace competition to promote innovation in space technology and foster transfer of developments into novel applications.

ESA – Europe

ESA has recognized the value of challenge-driven innovation actions for technology development, both to leverage traditional space and non-space actors, and has engaged in, as well as planned, a number of activities relating to ISRU.

Notably, ESA launched a sponsored challenge activity with the UK company, Metalysis, for testing a terrestrial process that electrochemically converts mineral oxides and ores in metallic alloy powders. This process technology can also be applied to lunar regolith, producing both oxygen and valuable metal alloys as products for ISRU. The ESA-Metalysis Grand Challenge was focused on developing process-monitoring systems that can interface with Metalysis's electrochemical cells and be applicable for the space environment also.

Currently, a challenge-based ISRU payload is under procurement at ESA with the objective to study the feasibility of extracting oxygen from the lunar regolith. The proposed challenge is embedded within a feasibility assessment part of the ISRU-DM mission study.

Additionally, a lunar prospecting technologies challenge is being prepared, with the possibility of having a successful concept developed for a potential flight opportunity. Such challenge activity will benefit from testing in analogue sites and aims at verifying specific technologies in the area of prospecting.

JAXA – Japan

The Team Japan Working Group, led by JAXA, Toyota, and Mitsubishi Heavy Industries, Ltd., was launched in August 2019 to study the theme of "lunar society pioneered by the manned pressurized rover". Four working groups and one session on the co-creation of a lunar society have been held to date, with about 100 companies registered.

KARI/KICT/KIGAM – South Korea

Although KARI is running a biannual CubeSat challenge to increase public interest and upgrade technological potential for smallsat design capabilities in academia, no prize challenge type activity on ISRU is currently ongoing. The challenge can be hopefully extended to moon and planetary missions in the near future.

LSA – Luxembourg

Although Luxembourg is always looking at new initiatives to develop ISRU, no prize challenge-type activity is currently ongoing. Challenges might be developed in the frame of the European Space Resources Innovation Center (ESRIC).

NASA – USA

Prizes and Challenges are extremely important to NASA in their ability to both 'cast the net wide' in search of innovative ideas and technologies, as well as engaging the public at large. The Centennial Challenge program is the largest challenge activity with NASA and is important to ISRU development plans and strategy. The regolith excavation challenge was initiated in 2007 and was successfully won by Paul's Robotics in 2009. The 3D Printed Habitat Challenge was performed in three phases, with the final phase of constructing a subscale habitat being completed in 2017, with the top prize being awarded to AI Spacefactory. Recently, NASA has initiated three ISRU-related Centennial Challenges

- Space Robotics Challenge: autonomous capabilities for space exploration missions

- CO_2 Conversion Challenge: convert CO2 into sugars
- Break the Ice Challenge: excavate icy regolith for processing and delivery of water

Besides Centennial Challenges, NASA also utilizes challenges to directly engage universities. NASA currently has three university-focused ISRU-related challenges: Lunabotics, Moon-Mars Ice Challenge, and the just-completed Breakthrough, Innovative, and Game-changing (BIG) ideas challenge 2020 aimed at exploration of lunar Permanently Shadowed Regions (PSRs), technologies that support ISRU in PSRs, and capabilities to explore and operate in PSRs.

UAESA – United Arab Emirates

The UAE Space Agency has recently started a program that supports the growth of private entity in the space sector utilizing incubation hubs and accelerators to encourage participation as well as running competitions. The UAE is always happy to support international companies to set up their entities in the UAE with everything that it has to offer.

UKSA – United Kingdom

The UK Space Agency has a number of funding programmes available to UK businesses that would allow ISRU specific applications, these include the CREST Technology Programme and National Space Technology Programme. These are competitive programmes that aim to support the development of exploration-specific technologies that both advance the UK position in space but also provide additional commercialisation opportunities, economic benefit, and spin-out.

POLICY/REGULATORY CHALLENGES

As space exploration and ISRU activities ramp up with a growing community of international actors, there is a gradual shift from agency-led to commercial activities in the new space economy. Internationally, there is a clear consensus that strong stewardship by space actors, guided by an internationally accepted framework, is the most responsible approach to the protection of extraterrestrial resources and our pristine deep space environment. Nations must show their leadership by putting an emphasis on planetary protection, ethical practices, and support for promoting science and open data sharing practices. Furthermore, the socio-economic benefits of SRU should be shared broadly by space actors in support of developing nations.

These key aspects have been highlighted in reports by working groups and committees discussing the potential development of an international framework on space resources activities; such as Building Blocks released by the Hague Space Resources Governance Working Group. These reports can serve as an informed approach and initial groundwork to the establishment of an international regulatory framework for ISRU activities that need to be addressed by an appropriate forum, such as, the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS). Since establishing international agreements through the UN is a slow process and the need for international agreements on the responsible use of space is needed urgently, the US released the Artemis Accords for international consideration. Based on the Outer Space Treaty, the Artemis Accords provide 10 provisions for how participating countries and their private sector players should conduct missions and operations in cislunar space.

Both the Hague Space Resources Governance Working Group and the Artemis Accords recognize that space resource activities need to have regulations in ownership and operations. Besides the overall benefits to human exploration and space commercialization, there is also a recognition that ISRU activities may bring certain risks and negative effects to space exploration (whether known or unknown) which require regulatory and in-situ protective measures, such as:

- Impact to pristine state of celestial body and to scientific integrity/data for:
    - Astro-geological surveys
    - Soil/rock samples
    - Scientific studies
    - Detection of bio-signatures
    - Cultural/Historic sites
- Exhaust gases, and lunar dust/debris from the mining operations, (ex: accumulating in the lunar exosphere)
- Chemical / biological contamination from Earth of a celestial body
- Resource consumption, depletion, and/or destruction of a celestial body
- Destabilisation of a planet's complex environmental system

Due to experience and lessons-learned in commercial terrestrial mining, it is recommended that space-faring nations and international regulatory bodies show their leadership through the establishment of a regulatory framework for space resources activities. The regulatory framework will be essential to guiding the best practices for resource assessment, extraction, distribution, and use as space resource activities gain momentum at the agency-level, and increasingly in the private sector of the space economy.

KEY FINDINGS AND RECOMMENDATIONS

Once all the sections of the ISRU Gap Assessment report were completed, the team was asked to review the work and define important findings that the assessment had identified. Based on the assessment and the findings, the team was also asked to define recommendations to stakeholders, decision-makers, and future developers that the team believed were essential to completing development and implementing ISRU capabilities into future human space exploration missions.

Key Findings

- ISRU is a disruptive capability and requires an architecture-level integrated system design approach from the start.
- The most significant impact ISRU has on missions and architectures is the ability to reduce launch mass, thereby reducing the size and/or number of the launch vehicles needed, or use the mass savings to allow other science and exploration hardware to be flown on the same launch vehicle. The next significant impact is the ability to extend the life of assets or reuse assets multiple times.
- The highest impact ISRU products that can be used early in human lunar operations (Table 7) are mission consumables including propellants, fuel cell reactants, life support commodities (such as water, oxygen, and buffer gases) from polar resources (highland regolith and water/volatiles in PSRs).
- While not in the original scope, evaluation of human Mars architecture studies and Table 7 suggest that there is synergy between Moon and Mars ISRU with respect to water and mineral resources of interest, products and usage, and phasing into mission architectures.
- A significant amount of work is underway or planned for ISRU development across all the countries/agencies involved in the study, particularly in the areas of resource assessment, robotics/mobility, and oxygen extraction from regolith (see Appendix B).
- While it appears each country/space agency has access to research and component/subsystem size facilities that can accommodate regolith/dust and lunar vacuum/temperatures, there are a limited number of large system-level facilities that exist or are planned.
- The assessment performed on the type and availability of lunar and Mars simulants for development and flight testing shows that 1. while simulants are available for development and testing, greater quantities and higher fidelity simulants will be needed soon, especially for polar/highland-type regolith, and 2) selection and use proper simulants is critical for minimizing risks in development and flight operations.
- Examination of resource assessment development and activities identified new efforts in refocusing technologies and instrumentation for lunar and Mars operations, and several missions to begin surface and deep assessment of resources are in development, especially to obtain maps of minerals on the lunar surface, surface topography, and terrain features, or to understand the depth profile of water and volatiles.
- While there is significant interest in terrestrial additive manufacturing/construction development, development for space applications has been limited and primarily under Earth-ambient conditions.
- Further research, analysis, and engagement are required to identify synergies between terrestrial mining and in-situ resource utilization (ISRU). Throughout the mining cycle and ISRU architecture, key areas for investigation include; dependence on remote, autonomous, and robotic operations; position, navigation, and timing systems; and energy technologies (e.g., small modular reactors and hydrogen technology).
- Stakeholder engagement is required between the terrestrial mining and space sectors to drive collaboration to identify and benefit from lessons learned from terrestrial innovations for harsh or remote operations.
- Long-term (months/years) radiation exposure limits for crew currently do not exist to properly evaluate radiation shielding requirements. These are needed to properly evaluate Earth-based and ISRU-based shielding options.

Recommendations

- To help advance ISRU development and use in future human exploration, it is recommended that countries/agencies focus on the defined Strategic Knowledge Gaps (SKGs) that have been identified as high priority for each of the 3 human lunar exploration phases described. Early emphasis should be placed on geotechnical properties and resource prospecting for regolith near and inside permanently shadowed regions.
- Since the access and use of in-situ resources is a major objective for human lunar and Mars exploration and the commercialization of space, locating, characterizing, and mapping potential resources are critical to achieving this objective. While work on resource assessment physical, mineral, and water/volatile measurement instruments are underway, and new orbital and lunar surface missions are in development or planned, a focused and coordinated lunar resource assessment effort is needed
- It is recommended that Science, ISRU, Human Exploration, and Commercial Space coordinate and work closely on SKG III.B Geodetic Grid and Navigation, SKG III.C Surface Trafficability, and SKG III.D Dust and Blast Ejecta to ensure surface activities and data collection are performed efficiently and safely.
- While short-duration lunar surface crewed missions can be completed with acceptable radiation exposure risk, it is recommended that long-term exposure limits be established and radiation shielding options (Earth and ISRU-based) be analysed as soon as possible to mitigate risks for sustained operations by the end of the decade.
- Long-term sustained operations will require a continuous flow of missions to the same location. While distance and placing of landers can be initially used to mitigate damage to already delivered equipment and infrastructure, an approach for sustained landing/ascent (in particular for reusable vehicles and hoppers) is needed. Dedicated plume-surface interaction analysis and mitigation technique development are recommended. It is also recommended that development of capabilities and establishment of landing/ascent pads be incorporated into human lunar architectures early to support sustained operations
- Experience from Apollo missions indicates that wear, sealing, and thermal issues associated with lunar regolith/dust may be a significant risk to long-term surface operations. Coordination and collaboration on dust properties/fundamentals, and mitigation techniques and lessons learned are highly recommended. This effort should also involve coordination and collaboration on the development, characterization, and use of appropriate lunar regolith simulants and thermal-vacuum facility test capabilities and operations for ground development and flight certification.
- To maximize the use of limited financial resources, it is recommended that the ISECG space agencies leverage the information presented in the report, in particular, the content of the "Technology Capture by WBS and Country/Space Agency portfolio" as a starting basis for further discussions on collaborations and partnerships related to resource assessment and ISRU development/operations.
- Collaboration and public-private partnerships with terrestrial industry, especially mining, resource processing, and robotics/autonomy are recommended to reduce the cost/risk of ISRU development and use. This includes establishment of an international regulatory framework for resource assessment, extraction, and operations, which are necessary to promote private capital investment and commercial space activities.
- The sustainable development aspects of the ISRU activity are recommended to be taken into account from the start of activity planning for the surface exploration of Moon and Mars.
- Aspects of reusing and recycling hardware are recommended to be taken into account from the design and architecture phase of mission planning. This will contribute to minimizing the exploration footprint (e.g. abandoned hardware) and therefore key towards sustainability.
- To accelerate the development of key technologies, close knowledge gaps, and expedite testing/readiness, it has been seen that the use of unconventional models, such as government-sponsored prize challenges can be effective innovation catalysts operationalizing the above recommendations, and ultimately, bringing ISRU to the Moon and onwards to Mars.

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APPENDICES

APPENDIX A: ACRONYMS

All space and government agencies in study

3D	three dimensional
AI	Artificial Intelligence
AMSM	Advance Materials, Structures, and Manufacturing
ANU	Australian National University
CLPS	Commercial Lunar Payload Services
DRRA	Destination Reconnaissance and Resource Assessment
DTVAC	Dirty Thermal Vacuum
EDL	Entry Descent and Landing
ESRIC	European Space Resources Innovation Centre
EVA	Extra-Vehicular Activity
EZ	Exploration Zone
g	grams
GAT	Gap Assessment Team
GCR	Galactic Cosmic Radiation
GER	Global Exploration Roadmap
GPoD	Global Point of Departure
IAWG	International Architecture Working Group
ISECG	International Space Exploration Coordination
ISM	In-Space Manufacturing
Isp	Specific Impulse
ISPCP	In-Situ Propellant and Consumable Production
ISRU	In-Situ Resource Utilization
ISRU-DM	In-Situ Resource Utilization Demonstration Mission
ISS	International Space Station
JHU-APL	John Hopkins University – Applied Physics Laboratory
kg	kilogram
KREEP	Potassium (K), Rare Earth Element (REE), Phosphorous (P)
LCROSS	Lunar Crater Observation and Sensing Satellite
LEAG	Lunar Exploration Analysis Group
LEAP	Lunar Exploration Accelerated Program
LEO	Low Earth Orbit
LRO	Lunar Reconnaissance Orbiter
LSIC	Lunar Surface Innovation Consortium
LSII	Lunar Surface Innovation Initiative
LSS	Life Support System
m^3	cubic meters
M^3	Moon-Mineral Mapper
MOXIE	Mars Oxygen ISRU Experiment
NDE	Non-Destructive Evaluation
ppb	parts per billion
ppm	parts per million
PSR	Permanently Shadowed Region
SAT	Special Action Team

SCLT	System Capability Leadership Team
SET	Space Environment Test
SKG	Strategic Knowledge Gap
SPE	Solar Particle Events
STMD	Space Technology Mission Directorate
TBD	To Be Determined
TRL	Technology Readiness Level
TWG	Technology Working Group
VIPER	Volatiles Investigating Polar Exploration Rover
vol%	volume percent
WBS	Work Breakdown Structure
wt%	weight percent
μg	micrograms

APPENDIX B: TECHNOLOGY CAPTURE BY WBS AND COUNTRY/AGENCY

		NASA		ESA	JAXA	CSA	CNES
WBS	**In Situ Resource Utilization**	**State of Art (SOA)**	**Current Technology Work**				
1	**Destination Reconnaissance and Resource Assessment**						
1.1	Site Imaging/Terrain Mapping				N/A		
1.2	Instruments for Resource Assessment						
	Instruments for Physical/Geotechnical Characterization	- Apollo instruments/ measurements - Prototype cone penetrometers and shear vanes - Terrestrial instruments	- COLDArm: Arm/scoop with cone penetrometer and microscope/camera - Boulder track imaging analyses - VIPER Trident auger meassure-while-drilling - VIPER wheel/soil interaction imaging	- PROSPECT mission (ProSEED instrument): Lunar drill (1m depth) Hammering mechanism Imaging System	-LUPEX (Lunar Polar Exploration) mission	Drills latest development DESTIN drill	Seismometer (SEIS), Permittivity probe
	Instruments for Mineral/Chemical Characterization	- Apollo instruments/ measurements - Science instruments for Mars	- NPLP Instrument selections - LSITP selections - DALI selections - BIG Ideas LIBS instrument - X-ray Spectrometer	- PROSPECT mission instruments: ITMS MSS GPS (+LES)	N/A	LIBS RAMAN	LIBS, RAMAN, ORBITRAP (Mass spectrometer)
	Instruments for Subsurface Ice Characterization	- Pulse neutron spec on Mars Curiosity Rover - RIMFAX GPR on 2020 Mars Perseverance Rover	- VIPER mission - neutron spec - NeuRover - neutron spec - Neutron Measurement at the Lunar Surface instrument - Cold Arm neutron spectrometer - ASU Neutron Spectrometer; - MSFC Neutron Spectrometer	- PROSPECT mission instruments: ITMS MSS GPS (+LES)	-LUPEX mission	Gravimeter, GPR, Neutron Spectrometer	Permittivity Probe
	Instruments for Water/Volatile Characterization	- SAM instrument on Curiosity rover - PVEx and OVEN at TRL 5/6	- LightWAVE Sample Heating with MS - PVEx with MS	- PROSPECT mission instruments: ITMS MSS GPS (+LES)	-LUPEX mission	Neutron Spectrometer	- SAM GC instrument on Curiosity rover, Micromega (Exomars-Mascot), Moma-GC (Exomars)
1.3	Orbital Site and Resource Evaluation						
	Surface imaging/mineralogy	- LRO - SELENE mission (Kaguya)	- Lunar Trailblazzer mission - Lunar Flashlight - Lunar IceCube	NOMAD (ExoMars heritage) Compact Hyperspectral Imager (HyperCube)	N/A	VMMO	Omega, MIRS (MMX)

		NASA		ESA	JAXA	CSA	CNES
WBS	**In Situ Resource Utilization**	**State of Art (SOA)**	**Current Technology Work**				
	Imaging in PSR	- LRO	- ShadowCam on Korean Orbiter	Scanning LIDAR unit RVS3000 (ATV, LIRIS-5), LEIA/PILOT scanning LIDAR.	N/A	Lyman Alpha, compact LiDARs, lights, stereo cameras	
	Higher Resolution Water/ Neutron Spectroscopy	- lunar Prospector - LRO - M3 on Chandraayn	- Artemis I Cubesats mission (LunaHMap, Lunar IceCube, Lunar Flashlight) - Lunar Trailblazzer mission		N/A	Neutron Spectrometer	
1.4	Local Surface Resource Evaluation						
	Integrated instruments for Processing and Site Selection	- Previous rpver science missions - RESOLVE/Resource Prospector development - ExoMars	- VIPER Mission/instruments - PRIME-1 Mission/instruments - SMD NPLP, LSITP, and DALI instrument/hardware selections - STMD instruments for ISPCP gaps 2.2.3, 2.2.4, 2.2.5, and 2.2.6 - Motors for dusty & extremely cold environments - BMG Gears and Motors - PPBE22 Dust Mitigation Projects: - Dev of Dust-Tolerant Seals & Performance Database - Lunar Dust Removal Tool - Electrodynamic Dust Shield	ExoMars rover science instruments	-LUPEX mission		Exomars instruments : Micromega, Moma- GC
	Mobility-Traversibility for Resource Assessment	- Resource Prospector/VIPER development - Previous science rover missions - ExoMars	- VIPER mission		-LUPEX mission	Rover development: 5kg, 30 Kg and 150 kg and 300Kg rovers) for lunar prospecting and science. Stuidies on going to perform a mission uncder CLPS to visit PSR with micro-rover.	
	Autonomy for Resource Assessment	- xGDS software for Resource Prospector operations and control - VIPER mission	- VIPER mission - CADRE coordinated rover operations	Rover autonomy developments for ExoMars, MSR-SFR.	-LUPEX mission	Advanced GNC development for rover, autonmous recovery systems development on-going inlcuding EVO	autonomous navigation (Exomars Rover), MSR-SFR french participation

		NASA		ESA	JAXA	CSA	CNES
WBS	In Situ Resource Utilization	State of Art (SOA)	Current Technology Work				
	Comm&Nav for Resource Assessment	- Mars science rover misisons - RESOLVE/Resource Prospector development	- VIPER mission	Lunar Communication and Navigation Service	-LUPEX mission	Telecommunications system studies and development for rovers	
1.5	Resource/Terrain/Environment Data Fusion and Analyses	- Model for Resource Prospector/VIPER mission	VIPER science ops development; SSERVI / RESOURCE project		-LUPEX mission	Modeling on-going for site selection and data analysis for traverse and mineralogy	
2	**Resource Acquisition, Isolation and Preparation**						
2.1	Gas Resource Collection, Separation, & Preparation						
	Mars CO2	- Subscale CO2 freezing and rapid cycle adsorption tests at NASA - SBIR Phase IIs on liquid and solid adsorption pumps at TRL 3/4 - Ionic liquid CO2 collection/separation for life support at TRL 4/5 - MOXIE compressor (1/200th scale for human mission)	-SBIR Phase II compressor at human mission scale - AirSquared - SBIR Phase II 2 Stage Adsorption - Umpqua - SBIR Phase II Liquid Adsorption - Pioneer Astronautics	Regenerative Fuel Cells for Mars Exploration (SOFC), excluding the activities for collection, separation and preparation of CO2 to feed the system. ACLS (LSR) technology: CCA subsystem	N/A		
	Mars Ar/N2	- Terrestrial seperation techniques	None		N/A		
2.2	Solid Resource Excavation/Acquisition						
	Granular	- CRATOS scoop belly - CSM/Astrobotic Bucketwheel - LMA/KSC Bucketdrum - GRC blade/scoop - GRC backhoe	- Fundamental Regolith Properties Project – regolith/excavation forces - ISRU Pilot Excavator (RASSOR) to flight prototype - RASSOR excavation implement challenge - BEAST autonomous excavator - University & Centennial Challenges: Robotic Mining Challenge, Space Robotics Challenge	- Development of In-situ regolith sampling Gear for Generous Excavation of Regolith (DIGGER) - System development for an innovative regolith excavation and beneficiation device in support of lunar ISRU	N/A	Prototyping for sample return collection and storage based upon HERACLES scenarios	

		NASA		ESA	JAXA	CSA	CNES
WBS	In Situ Resource Utilization	State of Art (SOA)	Current Technology Work				
	Hard - mineral and/or icy	- TRIDENT auger for small scale. TRL6 - RASSOR bucketdrum/ws scrapping TRL4 - PVEx for large scale. TRL6 - Orbitec Ripper TRL3 - KSC low force rock cutting experiments - MTU waterjet/dome	- STMD Fundamental Regolith Properties Project – regolith/ excavation forces - SBIR: Lunar Ice Mining Using a Heat-Assisted Cutting Tool, Sierra Lobo Inc. - STMD RASSOR - Michigan Tech. Univ. Waterjet/dome - STMD BEAST project -possible attachment device - Motors for dusty & extremely cold environments - BMG Gears and Motors	- PROSPECT mission (ProSEED instrument): Lunar drill (1m depth) Hammering mechanism Imaging System	N/A	Prototyping for sample return collection and storage based upon HERACLES scenarios DESTIN Drill TRL-6 development	
2.3	Resource Preparation before Processing						
	Size Reduction - Crushing/Grinding	- Crusher built by Canadian company (NORCAT) for RESOLVE	None	ExoMars crushing station	N/A		
	Mineral Seperation	- ilmenite/iron-oxide rich regolith seperation through tribocharging/electrostatic seperation by KSC	None		N/A		
	Size Sorting - Fractions	- SBIRs for regolith size sorting: TRL 2-3	- SBIR Phase II Sequential w/ Pioneer Ast. that includes size sorting	- ISRU-DM Transportation and Anti-Clog Lunar Regolith Technologies - System development for an innovative regolith excavation and beneficiation device in support of lunar ISRU	N/A		
2.4	Resource Transfer						
	Granular Material Transfer	- Auger devices - Pneumatic transfer	- STMD Fundamental Regolith Properties Project – vibratory regolith transfer	- ISRU-DM Transportation and Anti-Clog Lunar Regolith Technologies	N/A		

		NASA		ESA	JAXA	CSA	CNES
WBS	**In Situ Resource Utilization**	**State of Art (SOA)**	**Current Technology Work**				
	Gas Transfer		None	- PROSPECT mission (ProSPA instrument): Gas exchange pipe to Russian GAP instrument	N/A		
2.5	Resource delivery from Mine Site and Removal						
	Implement integration/operation &				N/A		
	Mobility-Traversibility for Resource Delivery/Removal	- Ground testing for VIPER 20 km goal; 8 hour PSR operation - Short duration analog field testing in 2008/2010/2012 - RASSOR testing in Swapworks soil bin	- ISRU Pilot Excavator (RASSOR) to flight prototype - Build and Excavation Autonomous System with Transportation (BEAST) autonomous excavator - University & Centennial Challenges: Robotic Mining Challenge, Space Robotics Challenge, EMC Challenge (formulation) - Day/night lunar rover obstacle avoidance and localization	- ISRU Pilot Plant excavator study	N/A	Rover utility protoytping and demonstration 2010 analogue mission with NASA	
	Autonomy for Resource Delivery/Removal	RASSOR - Demsonstrated basic autonomy with autodig routine and april tag point to point navigation	- ISRU Pilot Excavator (RASSOR) to flight prototype - Build and Excavation Autonomous System with Transportation (BEAST) autonomous excavator - University & Centennial Challenges: Robotic Mining Challenge, Space Robotics Challenge, Break the Ice Centennial Challenge	- ISRU Pilot Plant excavator study	N/A	Rover utility protoytping and demonstration 2010 analogue mission with NASA Demonstration of ORU concept studied and prototyped in part and used on the MSS would be required.	
	Comm&Nav for Resource Delivery/Removal	?	?		N/A		

		NASA		ESA	JAXA	CSA	CNES
WBS	**In Situ Resource Utilization**	**State of Art (SOA)**	**Current Technology Work**				
3	**Resource Processing for Production of Mission Consumables**						
3.1	Regolith Processing to Extract Oxygen						
	Physical/chemical	- Days of operation under ambient environments with simulants at sub-pilot scale (Hydrogen reduction and Carbothermal reduction)	- STMD Carbothermal Reduction reactor, feed/removal system, and reactant control – SNC, JSC, GRC with TP, PPBE22, & 2 SBIR - STMD Molten Regolith Electrolysis reactor, anode/cathodes and feed/removal system – KSC, MIT, Boston Metal with GCD & ECI - STMD Ionic Liquid Reduction and Electrolysis reactors for O2/metals – MSFC CIF and PPBE22; MSFC-UNLV Cooperative Agreement - STMD Plasma Hydrogen Reduction reactor and reactant control – KSC CIF and PPBE22 - SBIR Phase II Sequential with Pioneer Astronautics that includes CO/H2 Reduction and Metal formulation - STMD Fundamental Regolith Properties Project – regolith sealing and vibratory regolith transfer - STMD Regolith Valve project - STMD Dev of Dust-Tolerant Seals & Performance Database 2020 SBIR Phase I: - SBIR Solar Concentrator Oxygen Reactor with Continuous Heating and Extrusion of Regolith, (Carbothermal/Pyrolysis) Blueshift LLC - SBIR Ionic Liquid-Assisted Electrochemical Extraction of Oxygen from Lunar Regolith, Faraday Technology Inc. - SBIR Molten Regolith Electrolysis,	- ISRU Ground System Demonstrator: hydrogen reduction, carbothermal, molten-salt electrolysis. - ISRU-DM crucible/cathode/anode development - ISRU-DM high-temperature and dust resistant seals - ISRU-DM elecropumps and filters - ISRU-DM pre-forming of regolith (e.g. microwave heating) - Regenerative Ionic Liquids for O2 Production - Regolith pyrolisis experiments - Plasma processing of regolith - Hydrogen plasma reduction	N/A		Regolith MOE (Molten Oxide electrolysis) : Laboratoire de Génie Chimique University P Sabatier and Ecole des Mines d'Albi : oxygen extraction metal and silicium

		NASA		ESA	JAXA	CSA	CNES
WBS	In Situ Resource Utilization	State of Art (SOA)	Current Technology Work				
3.2	Regolith Processing to Extract Water						
	Surface-fed reactor	-ROxygen Reactor used for Mars soil: TRL 3 - Mars/Lunar soil auger dryer: TRL 3 - Mars soil open reactor dryer: TRL 3 - MTU Waterjet gypsum excavator: TRL 3	- STMD Auger Dryer project - UCF NIAC Phase I: Aqua Factorem ice crystal sifting - STMD Fundamental Regolith Properties Project - STMD Regolith Valve - STMD Motors for Dusty Env./Bulk Metallic Glass Gears		N/A		
	Subsurface enclosed reactor	- PVEx is TRL 6, but latest VF13 test showed limited water extraction	- PVEx	- PROSPECT mission (ProSEED and ProSPA instruments): Lunar drill (1m depth) Permitivity sensor Enclosed mechanism to transport regolith to sealed ovens for evolved gas analysis	N/A		
	Remote subsurface heating/vapor collection	- Lunar Microwave Heating: TRL 2-3 - CSM Thermal Mining: TRL 2-3	- LPMO NIAC Phase II: subsurface heating & volatile removal via microwave/RF/IR energy - 2020 SBIR Phase I: Thermal Management System for Lunar Ice Miners, Advanced Cooling Technologies Inc & ICICLE, Paragon		N/A		
3.3	Carbon Dioxide (CO2) Processing						
	CO2 to Oxygen	- MOXIE Solid Oxide Electrolyzer; 1/200th scale, 40 cycles, expected days of operation - Solid Oxide Electrolysis at TRL 4 by several vendors - Reverse Water Gas Shift (RWGS) at TRL 4; subscale, lab. env., and short duration - Bosch reactors for life support at TRL 4	- SBIR Phase II Redox Tolerant CO2 electrolysis - OxEon - BAA for CO2 & CO2/H2O Electrolysis with Methanation - OxEon	- Development of a Regenerative Fuel Cell System for Power Generation on Mars (SOFC) - ACLS (LSR) technology (O2 recovery from CO2) - Solar assisted oxygen and fuel production ("articicial photosysnthesis" based process, i.e.photoelectrocatalysis)	N/A		

		NASA		ESA	JAXA	CSA	CNES
WBS	In Situ Resource Utilization	State of Art (SOA)	Current Technology Work				
		- Enclosed plant-based food production systems -	- Ground based and various flight experiment. - Enclosed production systems (KSC and Academia)	- BIORAT 1 / ARTHROSPIRA B and C (photosynthetis in photobioreactors); BIORAT 2 - Higher plants based food production systems please note the interest to consider urine as a source of nutrients for biomass/plants, the overall concept being CO2 + nutrients= O2 + food products	N/A		
	CO2 to Methane (and Water)	- Sabatier reactor on ISS: CO2 rich; subscale to Mars ISRU - Microchannel Sabatier reactors through SBIRs - Subscale ISRU-related Sabatier reactor development and testing by SBIRs and NASA at TRL 3/4 - Industrial methanation reactors	- ISS Sabatier upgrade - BAA with OxEon with methanation reactor at human Mars missio scale	ACLS (LSR) technology (methane production)	N/A		
	CO2 to Hydrocarbon	-Fischer Tropsh reactors	None at this time		N/A		
		- Abiotic: Academic and start-up companies developing initial versions for commercial feedstock production. - Biological: Small start-up companies begining to make animal feed products	- NASA STRI CUBES - Physiochemical/Biological hybrid producing acetate. - ARC coop agreement Matthew Kanan at Stanford Univ. electrochemical production of acetate. - NASA Centennial CO2 Conversion Challenge attempting sugar production	Solar assisted oxygen and fuel production ("articicial photosysnthesis" based process, i.e.photoelectrocatalysis); fuel = long-chain hydrocarbons			

		NASA		ESA	JAXA	CSA	CNES
WBS	In Situ Resource Utilization	State of Art (SOA)	Current Technology Work				
	CO2 to Carbon	-Bosch reactors at TRL 3/4 -Methanation reactors for life support	None at this time	- Development of a Regenerative Fuel Cell System for Power Generation on Mars (SOFC) - Investigation of LOx-CO propellant combustion and production	N/A		
	CO2 to High Value Compounds (e.g., nutrients, pharmaceuticals)	- Commercial microbial and plant-based nutrient and pharmaceutical production systems - diverse scales and products	- STMD GCD - ARC Synthetic Biology - microbial nutrient production - STMD STRI - CUBES - plant and algal pharmaceutical production	- BIORAT 1 / ARTHROSPIRA B and C (photosynthetis in photobioreactors), for "algal" production (food supplement) - higher plants production - production of single-cell proteins (so called "solar foods")	N/A		
3.4	Water Processing						
	Water Electrolysis (Alkaline, PEM, SOE)	- ISS OGA Water Electrolysis - ISS Water Processor Assembly - Water Recycling Tech Demo on ISS - TRL 4/5 space PEM water electrolysis development: high pressure, cathode and anode feed, vapor-feed - Terrestrial water to hydrogen conversion for fuel cells/industry	- ISS OGA Water Electrolysis upgrade to remove dome and improve maintenance/sensors. - ISS Water Processor Assembly upgrades to Multifiltration bed redesign and operation modification - Regenerative Fuel Cell Project - Solid Oxide Electrolysis: 3 contracts with OxEon (SBIR Phase II, BAA, and TP) - Dirty Water Alkaline Electrolysis – Teledyne BAA - PEM Water Electrolysis/Clean-up – Paragon BAA - Lunar water simulant definition – CIF and Simulant Project - Lunar Propellant Production Plant (LP3) – Skyre TP - Advance Alkaline Reversible Cell/Dirty Water – pH Matter TP and ACO	- EL3 RFCS (PEM) - High-Pressure Water Electrolyser (SOFC) - Modular Water Electrolysis for Propulsion - Integrated Photo-Electrochemical Cell/fuel cell based water electrolysis (PEM) - ACLS water electrolyser (fixed alkaline)	N/A		

		NASA		ESA	JAXA	CSA	CNES
WBS	In Situ Resource Utilization	State of Art (SOA)	Current Technology Work				
	Water Capture/Storage	-ISS Water Processor Assembly - Lunar O2 production water vapor capture for PILOT and ROxygen 2008, and Carbothermal 2010	- GCD Fundamental Regolith Properties, Handling, and Water Capture	Manned space developed - condensing heat exchangers for water capture (Columbus); - Condensate water separator assemblies for water/gas separation - water tanks for storage (ATV, MPCV ESM, etc.)	N/A		
3.5	Instrumentation to Characterize Processing Performance			as above for surface characterisation, e.g. PROSPECT, hyperspectral imagers, multispectral imaging.			MOMA GC (exomars instrument)
	Instruments for mineral characterization (before/after)	- O2 extraction units at analog test sites - Terrestrial mining conveyors	None at this time	as above for surface characterisation, e.g. PROSPECT, hyperspectral imagers, multispectral imaging.	N/A		MOMA GC (exomars instrument)
	Instruments for chemical characterization			as above for surface characterisation, e.g. PROSPECT, hyperspectral imagers, multispectral imaging... Gas analysers: ANITA (FTIR)	N/A		MOMA GC (exomars instrument)
	Instruments for product purity characterization	- O2 extraction units at analog test sites - Life support air reguvination systems - mass spectrometers, tunable diode lasers, residual gas analyzers - terrestrial chemical plants	- GCD Laser Spectrometers for Impurity Analysis in ISRU Gas Streams - ISS Spacecraft Atmospheric Monitor - laser based - ISS Atmospheric Monitor	as above for surface characterisation, e.g. PROSPECT, hyperspectral imagers, multispectral imaging... Gas analysers: ANITA (FTIR) Water purity indicators with electroconductivity sensors	N/A		MOMA GC (exomars instrument)

		NASA		ESA	JAXA	CSA	CNES
WBS	In Situ Resource Utilization	State of Art (SOA)	Current Technology Work				
3.6	Product/Reactant Separation &						
	Chemical separation (adsorbent)	- adsorbants for oxygen, methane, and hydrogen drying before liquefaction - Permea membranes for CO/CO2 separation - Paladium-based electro-chemical hydrogen/gas separation	- SBIR Phase II for High Eff Sep/Recirc of CO2 - TDA - BAA on H2/CH4 Separation - Skyhaven		N/A		
	Passive separation (membranes)				N/A		
	Thermal separation (freezing/distillation)				N/A		
3.7	Contaminant Removal from Reagents/Products						
	Water Cleanup	- Water cleanup for ISS and life support systems	- Regenerative deionization	Membrane-based water treatment system	N/A		
	Gas Cleanup	- Non-regenerative gas cleanup demonstrated for subscale O2 extraction reactors - SBIR Phase II on H2S/HCl gas cleanup - Paragon	None at this time for ISRU	- ISRU Ground-Based Research: Oxygen Purification and Process Development			
3.9	Autonomous/Supervised Processing Operations						
4	**Resource Processing for Production of Manufacturing and Construction Feedstock**						
4.1	Regolith Manipulation for Manuf./Construction Feedstock	Lots of Earth-based concepts and technologies to draw upon. RASSOR provides one class of excavator for further evaluation in the context of this WBS element.	Some redesign activities are underway at KSC and GRC for implementing some of the sorting, transportation, and delivery tasks mentioned in this WBS, such as a Spiral Vibrating Plate Ramp.	- Sintering technologies payload study (solar/laser/microwave)			

		NASA		ESA	JAXA	CSA	CNES
WBS	In Situ Resource Utilization	State of Art (SOA)	Current Technology Work				
4.2	Resource Processing to Extract Metals/Silicon						
	Extract metals	Molten, molten flux, acid, and ionic liquid processing of regolith has been demonstrated at subscale in the lab.	- Molten Regolith Electrolysis reactor, anode/cathodes and feed/removal system – KSC, MIT, Boston Metal with GCD & ECI - Molten Regolith Electrolysis SBIR Phase I (NSF) – Lunar Resources - Ionic Liquid Reduction and Electrolysis reactors for O2/metals – MSFC CIF and PPBE22 - SBIR Phase II Sequential with Pioneer Astronautics that includes CO/H2 Reduction and Metal formulation - MSFC Cooperative Agreement with University of Mississippi; - MSFC Cooperative Agreement with Mississippi State University	- ISRU Ground-Based Research: metals as bi-product of molten-salt electrolysis process	N/A		
		Many large scale terrestrial companies use bioming for commercial metal production. Very large scale.	- Lynn Rothschild at NASA ARC biomining effort	BioRock, study of bioleaching and biofilm formation to demonstrate rare Earth element extraction in microgravity and Mars gravity			
	Extract silicon						
4.3	Resource Processing to Produce Plastics/Binders	- SBIRs on polyethylene production and Fischer Tropsh reactors for space plastic production	None at this time	Study on producing ink from organic waste for additive manufacturing Study on the production of cellulose-based manufacturing material			

		NASA		ESA	JAXA	CSA	CNES
WBS	In Situ Resource Utilization	State of Art (SOA)	Current Technology Work				
		- Biological: microbial production of biopolymers from methane and other organic substrates - Academic and small start-up companies.	- NASA STRI CUBES - advanced biopolymer production systems using ISRU methane - STTR - Mango Materials - biopolymers from ISRU methane	None at this time			
4.4	Autonomous/Supervised Processing Operations						
5	**Civil Engineering and Surface Construction**						
5.1	Site Planning and Design	Done extensively in development projects on Earth.	None to date as it applies to the lunar surface site measurements, etc. Some teams at NASA and in industry have begun considering this, such Lunar Site Planning & Design Team led by Ruthan Lewis at GSFC and David Wilson at Bechtel Corp.	- Conceiving a lunar base using 3D printing technologies - Moon Village study			
5.2	Site Preparation						
	Terrain Shaping: Area Clearing/Leveli	- NASA SOA is 100m x 100m sand dune area robotically leveled and graded by the NASA LANCE bulldozer bade at the Desert RATS analog testing in Moses Lake, WA. - CSA SOA is 3 autonomous rovers with blades clearing a circular landing pad area, building small berm, and extending road in analog testing in Hawaii 2010 -PIECES/NASA/Honeybee Robotics area clearing for landing pad construction	None at this time			Rover utility protoytping and demonstration 2010 analogue mission with NASA	

		NASA		ESA	JAXA	CSA	CNES
WBS	**In Situ Resource Utilization**	**State of Art (SOA)**	**Current Technology Work**				
	Surface Stabilization	-PIECES/NASA/Honeybee Robotics rover-based surface compaction after area clearing for landing pad Construction				Rover utility protoytping and demonstration 2010 analogue mission with NASA	
	Below Grade Operations and Support	- Regolith Advanced Surface Systems Operations Robot (RASSOR) that ha shown a 1 m trenching capability on Earth in regolith simulant. Metrics are a > 1 m deep trench with minimum width of 0.5 m. - Backhoe mounted on mobile platform and tested at analog sites	- RASSOR development to TRL 6 - Build and Excavation Autonomous System with Transportation (BEAST) in FY21 for modular, repairable platform with exchangable excavation/blade implements				
	Berm Construction	- 1 m high Berms have been built using the NASA LANCE bulldozer bade at the Desert RATS analog testing in Moses Lake, WA. 3m high berms are desired for a 50 m diameter landing/launch pad. Berm stability is desired with possible compaction or surface stabilization required.	None at this time	- D-Shape process (Study 3D Printed Building Blocks Using Lunar Soil)		Rover utility protoytping and demonstration 2010 analogue mission with NASA	
5.3	Construction Material Preparation						
	Size/Shape Manipulation	- SBIRs for regolith size sorting: TRL 2-3 - Crusher built by Canadian company (NORCAT) for RESOLVE	- SBIR Phase II Sequential w/ Pioneer Ast. that includes size sorting				

		NASA		ESA	JAXA	CSA	CNES
WBS	In Situ Resource Utilization	State of Art (SOA)	Current Technology Work				
	Component Mixing	- Multiple material bins and water conveyed and mixed as part of NASA/DOD in situ construction project (ACME) - Regolith, basaltic fibers, and binder mixed with terrestrial machinery and product pellets used in additive manufacturing	- In Situ Construction project (ICON/NASA) - MMPACT project			Rover utility protoytping and demonstration 2010 analogue mission with NASA	
	Conveyance	- Auger devices - Pneumatic transfer	- STMD Fundamental Regolith Properties Project – vibratory regolith transfer			Rover utility protoytping and demonstration 2010 analogue mission with NASA	
	Clean/Quality Control						
5.4	Construction Processess and Support			- Extrusion with phosphoric acid binder (Limited Resources Manufacturing) - Robotic manufacturing of fibrous structures in space (Advanced Concepts Team) - Basalt fibre reinforced geopolymer (Advanced Concepts Team)		Rover utility protoytping and demonstration 2010 analogue mission with NASA	
	Additive Construction	- NASA 3D Habitat Construction Centennial Challenge - Water/Concrete based additive manufacturing by NASA In-house - Regolith/Binder based additive manufacturing by NASA In-house	- ISM-Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) - In Situ Construction project (NASA/ICON)				
	Brickmaking/Press	- PIECES/NASA basaltic pads	- Continued work by PIECES on basaltic bricks and pads	- D-Shape process (Study 3D Printed Building Blocks Using Lunar Soil)			

		NASA		ESA	JAXA	CSA	CNES
WBS	In Situ Resource Utilization	State of Art (SOA)	Current Technology Work				
	Direct Sintering/Melting		- ISM-Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) Microwave Sintering Construction Capability (MSCC) Element and Direct Enegry Sintering Technologies - Concentrated Solar Regolith Additive Manufacturing [Colorado School of Mines]	- Solar sintering (3D printing of a model building block for a lunar base outer shell)			
	Supports/Structure/Framework		- Collaborative Manipulation for Space Exploration and Construction [Stanford University] - Lattice Reinforced Regolith Concrete for Lunar Infrastructure (NASA internal) - MMPACT				
	Joining						
	Post Construction Lining						
5.5	Horizontal Construction						
	Road Construction		- MMPACT Project, specifically MSCC Element				
	Foundation Construction						
	Landing/Launch Pad Construction	-PIECES/NASA/Honeybee Robotics area clearing, basaltic pads, and rover pad layout	- LSPACE student team/ICON - In-Situ Lunar Launch and Landing Pad Construction with Regolith and Thermoset Polymers (NASA Internal) - MMPACT Project, including MSCC Element	- Solar sintering (3D printing of a model building block for a lunar base outer shell) Potentially - Microwave sintering (Spaceship EAC)		Rover utility protoytping and demonstration 2010 analogue mission with NASA	
5.6	Vertical Construction & Shielding						
	Underground Structures	- RASSOR trenching 1 to 2 m below surface in regolith bed - Backhoe on mobile platform; Dessert RATS analog	- MMPACT ability to deposit raw regolith on structures designed to use regolith for radiation shielding				

		NASA		ESA	JAXA	CSA	CNES
WBS	In Situ Resource Utilization	State of Art (SOA)	Current Technology Work				
	Above Ground Unpressurized Structures	- NASA 3D Habitat Construction Centennial Challenge - Water/Concrete based additive manufacturing by NASA In-house - Regolith/Binder based additive manufacturing by NASA In-house - ICON demonstrated capability with Earth-made concrete	- Lunar Safe Haven study - ISM-Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) - In Situ Construction project (NASA/ICON) - Lattice Reinforced Regolith Concrete for Lunar Infrastructure (NASA internal)	- Radiation Shielding by ISRU for Habitats. - Solar 3D Printing (3D printing of a model building block for a lunar base outer shell) - D-Shape process (Study 3D Printed Building Blocks Using Lunar Soil) - Extrusion with phosphoric acid binder (Limited Resources Manufacturing) - Robotic manufacturing of fibrous structures in space (Advanced Concepts Team) - Basalt fibre reinforced geopolymer (Advanced Concepts Team)			
	Above Ground Pressurized Structures		- ISM-Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) - In Situ Construction project (NASA/ICON)				
5.7	Construction Waste/Recycling						
5.8	Maintenance & Life Cycle						
	In process Monitoring						
	Inspection and Compliance						
	Maintenance and Repair						
	Decommissioning/Salvage						
6	**In Space Manufacturing**						
6.1	Manufacturing Material Preparation			- Selective laser sintering of regolith - Lunar regolith fibre drawing			
	Metal powders						

		NASA		ESA	JAXA	CSA	CNES
WBS	**In Situ Resource Utilization**	**State of Art (SOA)**	**Current Technology Work**				
	Wire/Filament		- STMD Ionic Liquid Reduction and Electrolysis reactors for O2/metals – MSFC CIF and PPBE22				
	Polymers		- STMD Ionic Liquid Reduction and Electrolysis reactors for O2/metals – MSFC CIF and PPBE22				
	Ceramics						
	Regolith		MIS RegISS Experiment				
6.2	Manufacturing Processes and Support			- Basalt fibre reinforced geopolymer cement made from lunar regolith simulant - MoonFibre			
	Additive Manufacturing		MSFC FabLab including TechShot and MIS Vulcan	- Additive manufacturing of metallic by-product from oxygen extraction - Lithographic ceramic additive manufacturing (Conceiving a lunar base using 3D printing) - Regolith slurry extrusion printing			
	Subtractive Manufacturing		MIS Vulcan				
	Composite Manufacturing		MSFC SBIR with Geocomposites	- Robotic manufacturing of fibrous structures in space			
	Near Net Shape		MIS Vulcan	- Aluminium casting using regolith molds			
6.3	Part Finishing/Verification			- Additive manufacturing of functionally graded ceramics with in-situ resources			
	CNC Milling		MIS Vulcan				
	Polishing/Deburring						
	Heat Treatment		TechShot FabLab				
	Coatings						

		NASA		ESA	JAXA	CSA	CNES
WBS	**In Situ Resource Utilization**	**State of Art (SOA)**	**Current Technology Work**				
6.4	Part Joining						
	Welding		MSFC Additive Friction Stir Welding				
	Fastners/adhesives						
6.5	Assembly						
	Adhesives						
	Mechanical						
	Welding		MSFC Additive Friction Stir Welding				
	Pick and Place						
6.6	Manufacturing Waste Recycling						
	Polymer		MSFC ISM projects with TUI (Refabricator) and MIS (Redux or MIS Recycler)				
	Metal		MSFC Additive Friction Stir Welding				
	Other materials						
6.7	Maintenance & Life Cycle						
	In process Monitoring		MSFC FabLab including TechShot and MIS Vulcan				
	Inspection and Compliance		MSFC FabLab including TechShot and MIS Vulcan				
	Maintenance and Repair						
	Decommissioning/Salvage			- Recycling of Hardware for Moon and Martian Settlement - Recycling module for all waste in microgravity, enabling reuse for 3D printing for future exploration			

		ASI	KARI	ASA/CSIRO		UKSA	DLR
WBS	**In Situ Resource Utilization**			**SoA in Terrestrial Context**	**Spin-in + Development**		
1	**Destination Reconnaissance and Resource Assessment**						
1.1	Site Imaging/Terrain Mapping		- Lunar Terrain Mapping DB Platform and Portable Mapper (KARI, KIGAM) - Lunar Imaging/Mapping Visualization System (KARI)				
1.2	Instruments for Resource Assessment						
	Instruments for Physical/Geotechnical Characterization		- KPLO mission (LUTI(Lunar Terrain Imager, KARI) POLCAM(Polarization Camera, KASI), KMAC(magnetormeter, lunar surface magnetometer KHU) - Lunar Space environment Monitor, lunar surface radiation dosimeter, Dust Camera (KASI)	- Magnetometer (NRM, AMS) - Magnetic Susceptability - Density (gravemetric) - LF EM (Susceptibility) - Radiometrics (passive and active) - Hylogger (integrated minerology assessment) - Borehole radar imaging technologies	- Miniturisation, customisation, integration - Hardening and demonstrations through evaluations at terrestrial analog sites		InSight mission HP3 instrument, hammering mechanism, assessment of Mars case, ongoing development
	Instruments for Mineral/Chemical Characterization	- Ma-MISS (Mars Multispectral Imager for Subsurface Studies) for mineral characterization, hosted by the drill system of the Exomars 2020 rover	- KPLO mission (KGRS, gamma-ray spectrometer) (KIGAM) - X-ray spectrometer (KIGAM) - LIBS (KIGAM, KIMM)	PGNAA (neutron) sensor for elemental resource characterisation	- Pyroelectric generator research for very small size, small power configurations suitable for ISRU resource assessment	ProSPA	ProsPA sample oven/tapping station, Max-Planck Institute for Solar Systems Research
	Instruments for Subsurface Ice Characterization			- Broad class of NDT instrmentation methods - GPR (Ground-based) imaging systems spanning 100MHz - 8GHz - X-ray Fluorescence (XRF), portable - Laser Induced Breakdown Spectroscopy (LIBS) - Microseismics and Seismic methods - Novel, high-accuracy	- Miniturisation, customisation, integration - Hardening and demonstrations through evaluations at terrestrial analog sites	Lunar Thermal Mapper ProSPA	HP3 penetration mechanisms

		ASI	KARI	ASA/CSIRO		UKSA	DLR
WBS	In Situ Resource Utilization			SoA in Terrestrial Context	Spin-in + Development		
	Instruments for Water/Volatile Characterization			- Portable Terahertz imaging systems - Percometer (electromagnetic dielectric measurement tool)	- Evaluation for demonstrations through evaluations at terrestrial analog sites for ISRU resource assessment	Lunar Thermal Mapper ProSPA	ProsPA sample oven/tapping station, Max-Planck Institute for Solar Systems Research
1.3	Orbital Site and Resource Evaluation						
	Surface imaging/mineralogy		lunar minerological analysis using M3 data (KIGAM)				
	Imaging in PSR						telerobotic and automation
	Higher Resolution Water/ Neutron Spectroscopy		- Neutron Spectrometer (KIGAM, KASI)			- Lunar Thermal Mapper (Lunar Trailblazer)	
1.4	Local Surface Resource Evaluation						
	Integrated instruments for Processing and Site Selection			- Broad class of optical camera instrumentation (thermal, visible, hyperspectral) - Radar-based imaging (polarmetric, interferometric)	Hardening and demonstrations through evaluations at terrestrial analog sites	- PanCam (ExoMars) ProSPA	telerobotics and autonomy
	Mobility-Traversibility for Resource Assessment			- Integrated mapping and localisation based on aided sensing and navigation technologies - Robust lidar and radar imaging technologies for zero-illumination conditions	- Exploring opportunities for miniturisation and integration	- Mars Sample Return Sample Fetch Rover	- mobility derived from MASCOT (Mobile Asteroid Surface Scout) lander mission during Hayabusa-2, participation JAXA MMX;

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WBS	**In Situ Resource Utilization**			**SoA in Terrestrial Context**	**Spin-in + Development**		
	Autonomy for Resource Assessment			- Integrated mapping and localisation based on aided sensing and navigation technologies - Inertial navigation solution - Robust lidar and radar imaging technologies for zero-illumination conditions - Remote operations capabilities for industrial	- Exploring opportunities for miniturisation and integration - Hardening and ISRU-centric demonstrations through evaluations at terrestrial analog sites	"Brain" TubeHunter Autonomy for SFR	Rover autonomy in DLR/ROBEX project ROBEX
	Comm&Nav for Resource Assessment			- Integrated mapping and localisation based on aided sensing and navigation technologies - Inertial navigation solutions - Robust lidar and radar imaging technologies for zero-illumination conditions	- Exploring opportunities for miniturisation and integration - Hardening and ISRU-centric demonstrations through evaluations at terrestrial analog sites		autonomy and communication
1.5	Resource/Terrain/Environment Data Fusion and Analyses			- Broad range of multi-scale integration packages to develop real-time maps for mining extraction	- Adaption and demonstration through terrestrial analogue demonstration		
2	**Resource Acquisition, Isolation and Preparation**						
2.1	Gas Resource Collection, Separation, & Preparation						
	Mars CO2						
	Mars Ar/N2						

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2.2	Solid Resource Excavation/Acquisition						
	Granular	- Prototyping of sampling tool suited to very fast sampling in presence of basically no or very low gravity (LDO) - Prototyping of regolith excavation systems for lunar ISRU missions (OHB-I)				DROD	
	Hard - mineral and/or icy	- DEEDRI (Deep Drill) project (LDO) - L-GRASP (Lunar Generic Regolith Acquisition/Sampling Paw) (LDO) -EXOMARS 2020 rover Drill System (LDO) - Prototypes of drilling and sampling tools fro Mars and Moon missions (LDO)				Plasma Drill concept	
2.3	Resource Preparation before Processing						
	Size Reduction - Crushing/Grinding		-Typical crushing/grinding machine / Jaw, cone and hammer crusher, ball and disc mill (Lab scale) (KIGAM) - Monitoring system is designed for Monitoring grinding process using vibration & acustic signal measured from grinding process (KIGAM)				
	Mineral Seperation		- Dry separation process: magnetic & electrostatic separation mechaine (KIGAM)	- Radiometric sensing for material beneficiation and sorting			
	Size Sorting - Fractions	- Prototyping of particle size separation systems for Lunar regolith processing (OHB-I)					

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WBS	**In Situ Resource Utilization**			**SoA in Terrestrial Context**	**Spin-in + Development**		
2.4	Resource Transfer						
	Granular Material Transfer	- Prototyping of lunar regolith handling systems for Lunar ISRU missions (OHB-I)				Robotic arms: LARAD, RISMA, LOCARM. - ACTS Autonomous Cache Transfer System (MSR Sample Fetch Rover)	
	Gas Transfer						ProsPA sample oven/tapping station, Max-Planck Institute for Solar Systems Research
2.5	Resource delivery from Mine Site and Removal						
	Implement integration/operation &						
	Mobility-Traversibility for Resource Delivery/Removal						expertise MASCOT and follow-ups
	Autonomy for Resource Delivery/Removal			- Industry-hardened resource handling and stockpiling methods - Online monitoring of supply chain processes (status and grade)		"Brain" PRO-ACT	autonomy and telerobotics, note: dust mitigation as gap in both ISECG reports
	Comm&Nav for Resource Delivery/Removal						
3	**Resource Processing for Production of Mission Consumables**						
3.1	Regolith Processing to Extract Oxygen						
	Physical/chemical					Molten Salt Cambridge FFC process Microwave sintering	
3.2	Regolith Processing to Extract Water						
	Surface-fed reactor						
	Subsurface enclosed reactor						ProsPA sample oven/tapping station, Max-Planck Institute for Solar Systems Research

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WBS	**In Situ Resource Utilization**			**SoA in Terrestrial Context**	**Spin-in + Development**		
	Remote subsurface heating/vapor collection						
3.3	Carbon Dioxide (CO2) Processing						
	CO2 to Oxygen	Ground-based BLSS study for the use of different organisms with in-situ resources (regolith, water, gases) and crew waste (ReBUS)					
	CO2 to Methane (and Water)						
	CO2 to Hydrocarbon	Ground-based BLSS study for the use of different organisms with in-situ resources (regolith, water, gases) and crew waste (ReBUS)					
	CO2 to Carbon						
	CO2 to High Value Compounds (e.g., nutrients, pharmaceuticals)						
3.4	Water Processing						
	Water Electrolysis (Alkaline, PEM, SOE)						
	Water Capture/Storage	Realization of a prototype of flexible containers for water storage and maintenance of its chemical, physical, and microbiological properties (PERSEO-PErsonal Radiation Shielding for intErplanetary missiOns)					

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WBS	**In Situ Resource Utilization**			**SoA in Terrestrial Context**	**Spin-in + Development**		
3.5	Instrumentation to Characterize Processing Performance						
	Instruments for mineral characterization (before/after)						
	Instruments for chemical characterization						
	Instruments for product purity characterization						
3.6	Product/Reactant Separation & Recirculation						
	Chemical separation (adsorbent)						
	Passive separation (membranes)						
	Thermal separation (freezing/distillation)						
3.7	Contaminant Removal from Reagents/Products						
	Water Cleanup						
	Gas Cleanup						
3.9	Autonomous/Supervised Processing Operations						
4	**Resource Processing for Production of Manufacturing and Construction Feedstock**						
4.1	Regolith Manipulation for Manuf./Construction Feedstock						
4.2	Resource Processing to Extract Metals/Silicon						
	Extract metals		- Reactor and relevant system for molten salt electrolysis (KIGAM) - Reactor and relevant system for reduction of oxides using H2 gas (KIGAM)			Molten Salt Cambridge FFC process Microwave sintering	
	Extract silicon						
4.3	Resource Processing to Produce Plastics/Binders						

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4.4	Autonomous/Supervised Processing Operations			Remote monitoring and control technology to manage mission critical mining assets in complex operational environments	Adaption of remoteand autonomous systems to support ISRU build up and related foundation services		specialization of telerobotics and autonomy for ISRU tasks
5	**Civil Engineering and Surface Construction**						
5.1	Site Planning and Design		- Rover-based mapping system under low illumination condition (TRL4) (KICT) - 10kg, 1m, 50W drilling system able to penetrate 2~4MPa(UCS) ice (KICT)				EU/H2020 consortium: concurrent engineering between fundamental materials resesarch and civil engineering
5.2	Site Preparation						
	Terrain Shaping: Area Clearing/Leveling/Grading			- Stockpiling mapping and design methods			
	Surface Stabilization						EU/H2020 levelling by sintering
	Below Grade Operations and Support						
	Berm Construction						
5.3	Construction Material Preparation						
	Size/Shape Manipulation						
	Component Mixing						
	Conveyance						
	Clean/Quality Control						
5.4	Construction Processess and Support						

		ASI	KARI	ASA/CSIRO		UKSA	DLR
WBS	**In Situ Resource Utilization**			**SoA in Terrestrial Context**	**Spin-in + Development**		
	Additive Construction						EU/H2020 RegoLight: additive manufacturing of building elements with internal structure, demonstration from solar sintering and engineering; project MOONRISE, TU Braunschweig: laser
	Brickmaking/Press						ESA/DLR: oven sintering of brick from regolith simulants
	Direct Sintering/Melting		- Microwave sintering of lunar regolith simulant (TRL3) (KICT)				EU/H2020 RegoLight, sintering regolith with solar radiation: process parameters and control, material and product analysis, concurrent design in civil engineering, scenario built on existing sintering technology and reliability; ultimate strength of concrete from regolith sintering, TRL 4-5 material strength if gypsum
	Supports/Structure/Framework						EU/RegoLight: building elements without necessity for scaffold

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WBS	In Situ Resource Utilization			SoA in Terrestrial Context	Spin-in + Development		
	Joining						EU/RegoLight: assessment of production tolerances of building elements and consequence for joining
	Post Construction Lining						
5.5	Horizontal Construction						
	Road Construction						
	Foundation Construction						
	Landing/Launch Pad Construction						EU/RegoLight consortium: rover-based solar sintering concept
5.6	Vertical Construction & Shielding						
	Underground Structures						
	Above Ground Unpressurized Structures & Shielding						EU/RegoLight, solar sintering with regolith
	Above Ground Pressurized Structures						
5.7	Construction Waste/Recycling						
5.8	Maintenance & Life Cycle						
	In process Monitoring						
	Inspection and Compliance						
	Maintenance and Repair						
	Decommissioning/Salvage						
6	**In Space Manufacturing**						
6.1	Manufacturing Material Preparation						
	Metal powders						DLR: 3D printing from metallic powders in low and zero gravity
	Wire/Filament						

WBS	In Situ Resource Utilization	ASI	KARI	ASA/CSIRO SoA in Terrestrial Context	ASA/CSIRO Spin-in + Development	UKSA	DLR
	Polymers		- geopolymer cement made from lunar regolith simulant (KIGAM)				DLR: 3D printing from polymeric powders in low and zero gravity
	Ceramics						
	Regolith						MASON (DLR) MICS (NASA) collaboration to study cement/concrete solidification on ISS
6.2	Manufacturing Processes and Support						
	Additive Manufacturing	The Portable on-Orbit Printer 3D (POP3D) implements the Fused Deposition Modelling (FDM) process for the fabrication of parts using the PLA thermoplastic polymer					
	Subtractive Manufacturing						
	Composite Manufacturing						
	Near Net Shape						
6.3	Part Finishing/Verification						
	CNC Milling						
	Polishing/Deburring						
	Heat Treatment						MaRS initiative (Manufacturing Research in Space), German universities production engineering
	Coatings						
6.4	Part Joining						
	Welding						
	Fastners/adhesives						

		ASI	KARI	ASA/CSIRO		UKSA	DLR
WBS	**In Situ Resource Utilization**			**SoA in Terrestrial Context**	**Spin-in + Development**		
6.5	Assembly						
	Adhesives						
	Mechanical						
	Welding						
	Pick and Place						
6.6	Manufacturing Waste Recycling						
	Polymer						
	Metal						
	Other materials						
6.7	Maintenance & Life Cycle						
	In process Monitoring						
	Inspection and Compliance						
	Maintenance and Repair						
	Decommissioning/Salvage						